



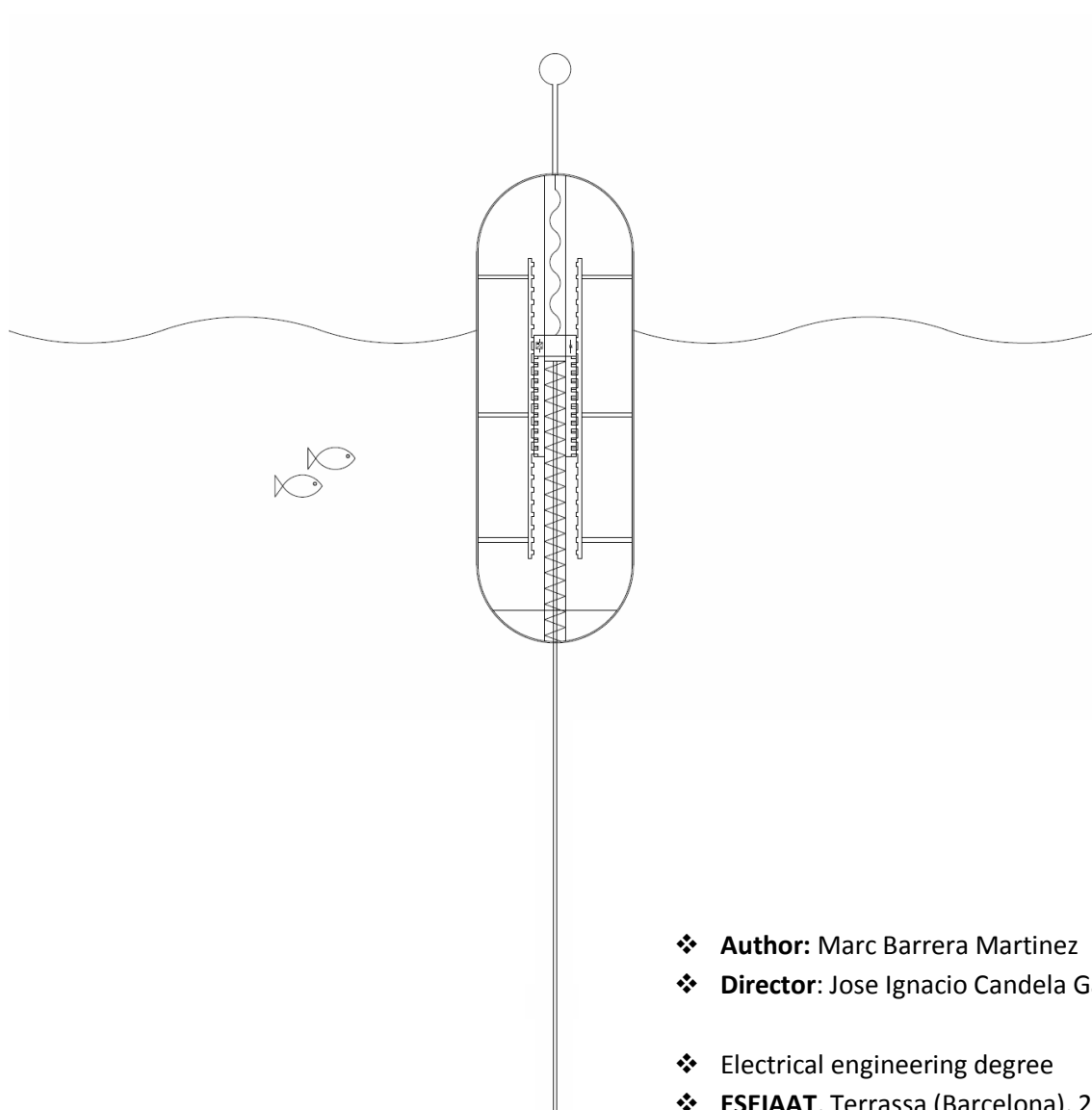
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Final degree project

Design of reluctance generator for an improved wave energy system



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Abstract

As nowadays the electrical generation sources are moving so fast from fossil to renewable energy sources, is crucial to develop these new technologies and improve it to reach an equivalent energy sources as the old ones, but keeping the environment and responsibility in mind.

The project's goal is based on design an electrical generator powered by ocean waves motion with simplicity, reliability, price and versatility on mind, for that reason a linear reluctance generator will be implemented to a reliable point absorber device adding to, this well tested generator typology, the latest technology eliminating the problematical linear to rotatory motion converters used until today on this generators, and improving it even more with a full electronic control of the electrical generation.

The design is done from scratch to the final design on all the generator components: mechanic, electric, magnetic, thermic and electronic parts making this project a set of different projects, linked between them.

On the design a collection of different knowledges and technology was used, on mechanical stage a classic physical and movement theories are used but on electromagnetic stage a new ones technology as finite elements software and electronic simulation software is employed to obtain the most accurate solutions.

Finally an all in one device is obtained making it a good alternative to generate renewable energy on places where the ocean wave energy is a good option as energy source, allowing to complement the already used generation methods or as standalone one, providing electricity on isolated coastal zones.

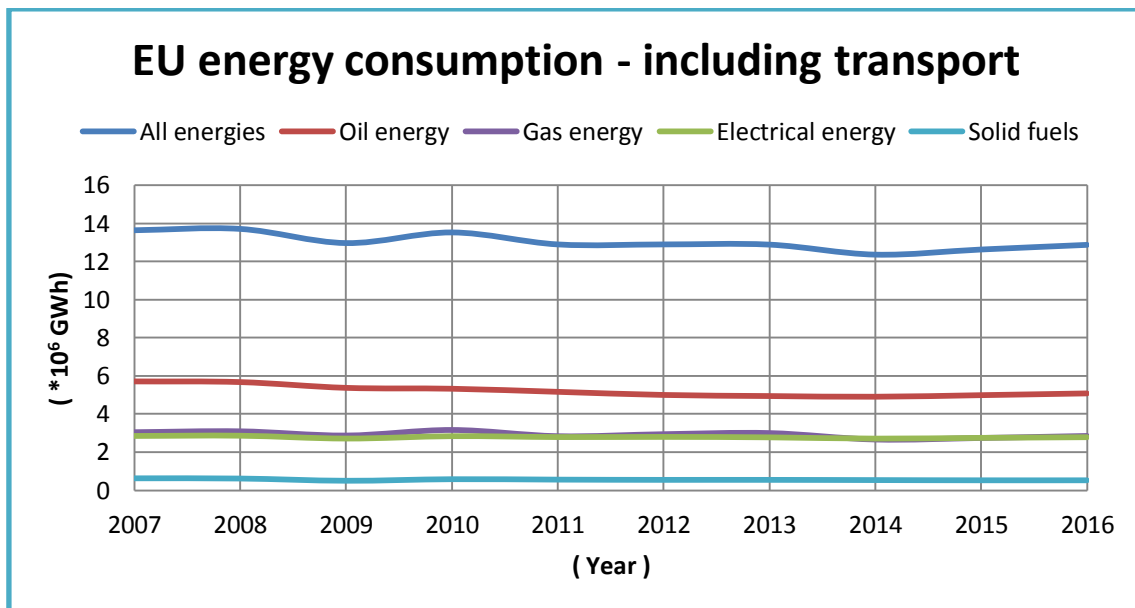
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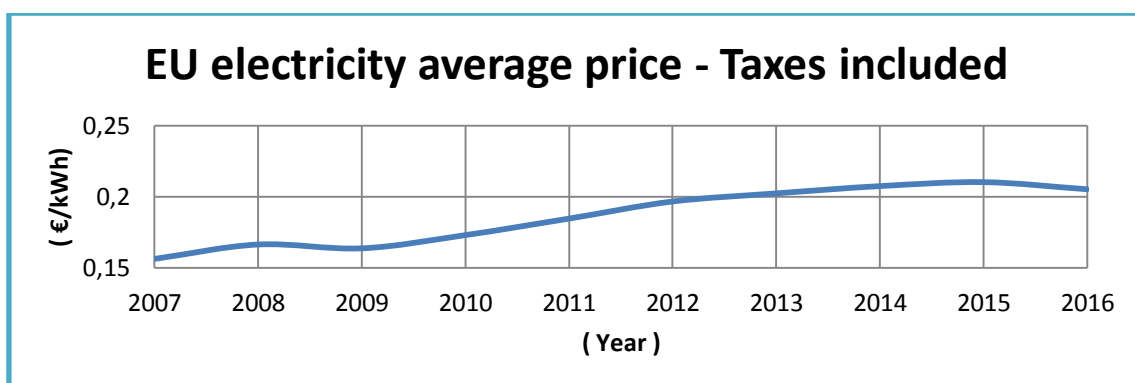
1 Introduction

1.1 Renewable energies and environment situation

Electrical energy it is one of the most used nowadays energies in the world because it is a fast, clean, low losses and reliable generation, transportation and consumption system. Especially it is the best way to transport energy from a source to a consumer that we actually know.



Statistic 1: Energy consumption (Source: Eurostat European Statistics)



Statistic 2: Electricity price (Source: Eurostat European Statistics)

But we have a problem at the source, electricity it is not a primary source, for that reason we need to generate it from other primary energy sources. There are two main ways of primary sources:

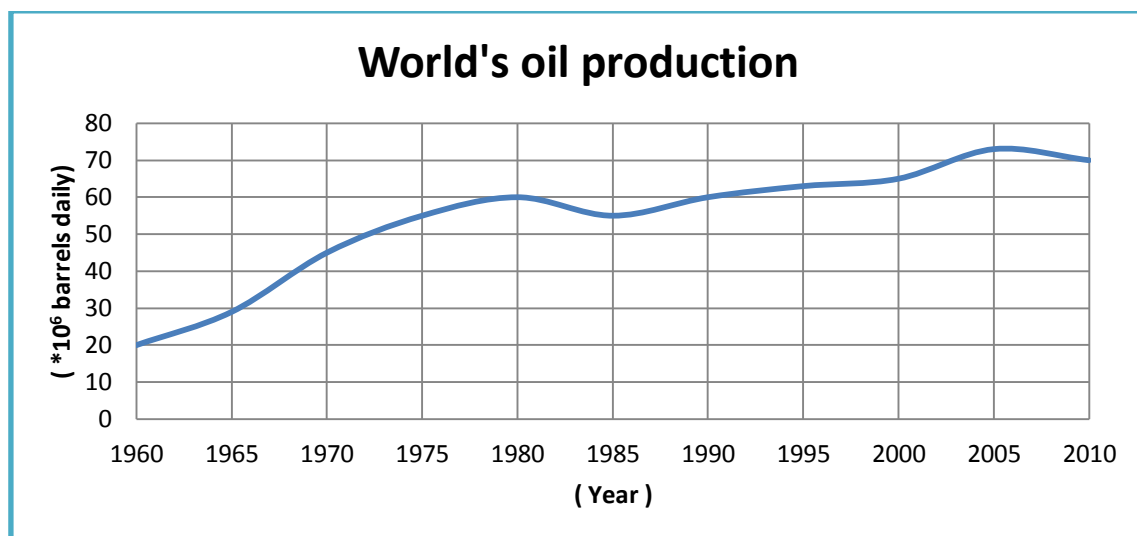
Renewables: Energy sources generated in continuous mode by the sun radiation or others sustainable methods. Its use does not become an environment problem. This is a development industry and it is emerging nowadays, for this reason only 3 are commonly used.

- **Solar:** Energy converted directly from sun radiation
- **Eolic:** Wind energy generated by thermal gradients on the ground / seas
- **Hydraulic:** Water potential energy generated by rains
- **Others:** Geothermal, marine, biomass

Non-renewables: Energy sources that proceeding from sun energy was accumulated over the centuries and now we can use it with at high power delivery. They are not renewable and exists only a certain amount on Earth. The major problem becomes when they are used it as thermal energy, burning it to obtain the chemical energy; it produces a high contamination effect on the environment that we cannot maintain longer.

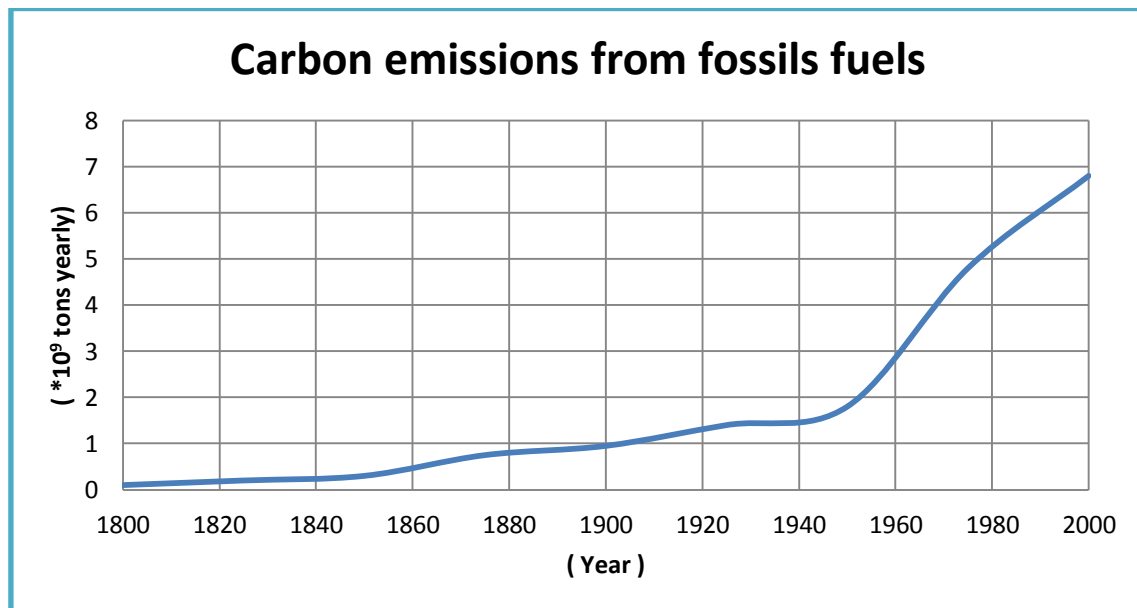
- **Fossils:** The most used energy source in the world, it can be from gas, coal or oil. It is produced by concentration of lots died life forms in the past.
- **Nuclear fission:** Atomic energy present in some reactive materials like Uranium. It is dangerous, polluting (on their wastes), and there are low reservoirs.

Now we are near to the oil's peak, it is based on the Hubbert peak theory and the consumption/discover oil resources ratio, and it means that in a near future the oil will become unavailable to produce an economical energy.



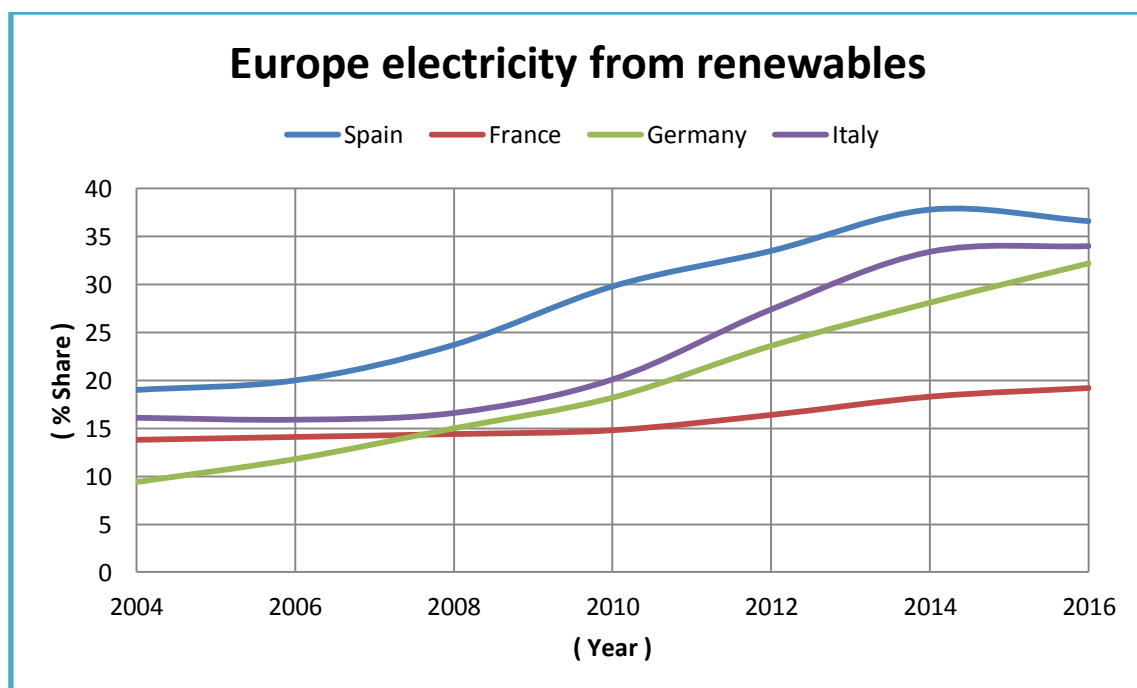
Statistic 3: Oil production (Source: IEA International Energy Agency - database 1960–2009)

Other important negative hit of fossil's sources is the CO₂ generation. CO₂ is one of the most important factors of the hazardous greenhouse effect, as we can see on the next graph these polluting emissions must be controlled soon to stop rising it:



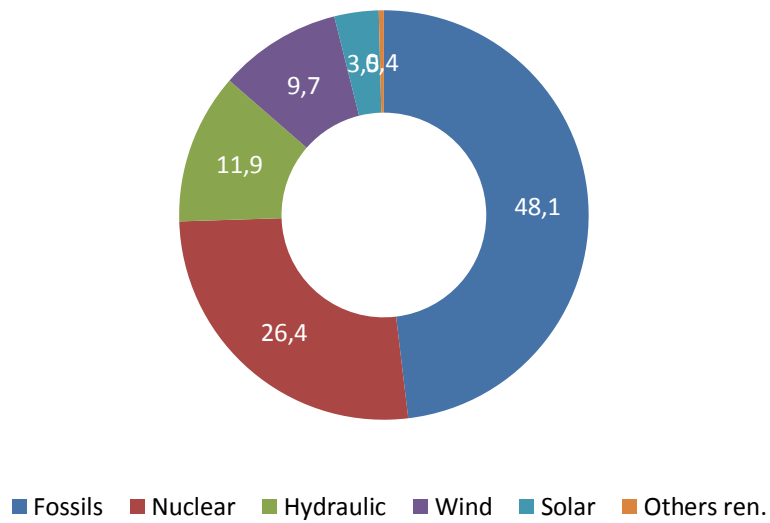
Statistic 4: Carbon footprint (Source: CDIAC Carbon Dioxide Information Analysis Center - 1800-2007)

As we can see, humanity is changing their energy sources from non-renewables to renewables at an increasing rate over the years, specially forced by the decreasing amount of fossils reserves, increasing prices, and greenhouse effect.



Statistic 5: Europe's renewables usage (Source: Eurostat European Statistics)

Europe 2015 electricity sources (%)



Statistic 6: Europe's electricity distribution (Source: Eurostat European Statistics)

For these reasons, renewables energies are the only possible choice to generate electricity in our future and for that reason we need to put our efforts on develop and implement these energies on our societies.

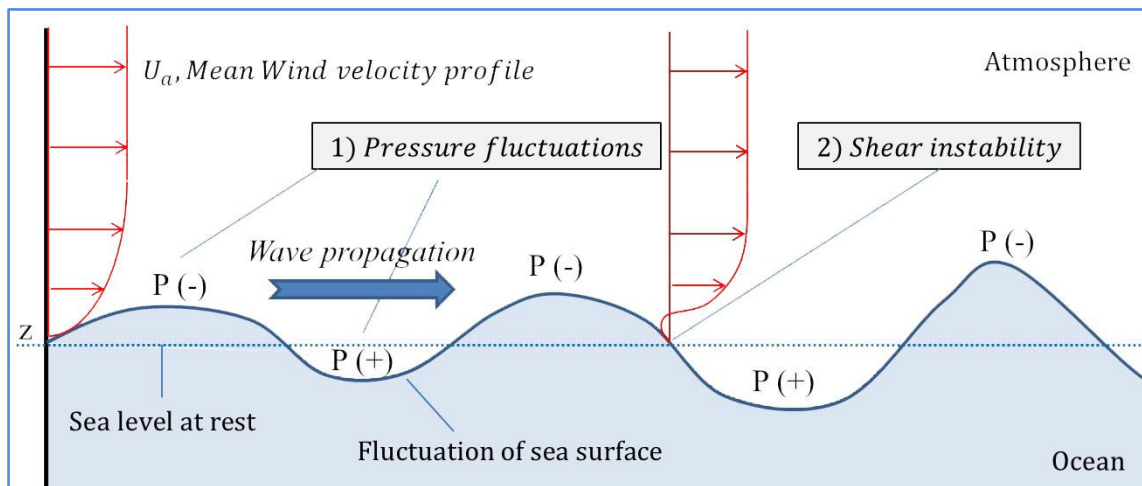
1.2 Wave's energy introduction

The wave's energy used as a primary source to generate electricity is not much used, but is on development and has a great potential on the next years.

The wave's energy is generated by the wind and the wind is generated by the sun, that means that wave's energy is a 100% renewable energy produced continuously every day.

Over the oceans and seas the wind transfer part of their energy to the water creating the waves, this is how it does starting from a flat sea surface:

The wind creates different pressures on the water surface, it creates the firsts small ripples on the surface and after that the wind will directly make the wave grow.



Picture 1: Wave generation (Source: https://en.wikipedia.org/wiki/Wind_wave)

There are 3 important factors that develop the final wave energy, the wind speed, the uninterrupted distance where wind blows and the duration.

Wind speed (km/h)	Distance (fetch) (km)	Duration (h)	Height* (m)	Wave length (m)	Period (s)	speed (km/h)
19	19	2	0,27	8,5	3	10,2
37	139	10	1,5	33,8	5,7	21,4
56	518	23	4,1	76,5	8,6	32
74	1313	42	8,5	136	11,4	42,9
92	2627	69	14,8	212,2	14,3	53,4

Statistic 7: Comparison between wind and final waves sizes (Source: https://en.wikipedia.org/wiki/Wind_wave)

* Wave's height are always measured from trough to crest

As we can see the most important factors are the wind speed and the size of the surface on it blows, for that reason the highest energies are on oceans and specifically on strong wind areas.

Waves accumulate energy in two ways, kinetic and potential, each one contributing 50% of wave's total energy. Wave energy and power are calculated as follows:

$$E = \frac{1}{16} \rho g H^2 \quad P = \frac{1}{16} \rho g H^2 c$$

c (group velocity) is equal to:

$$c = \frac{g}{4\pi} T$$

Finally we can calculate the total power for a metre of wavefront as:

$$P = \frac{\rho g^2}{64\pi} H^2 T \approx \left(0,5 \frac{kW}{m^3s}\right) H^2 T$$

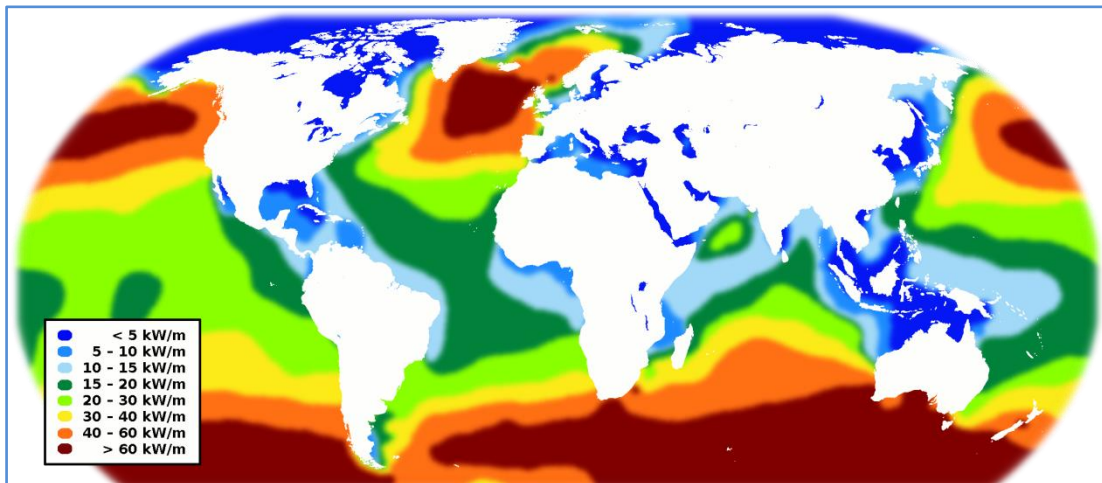
P=Power (kW)

H=Significant wave height (m)

T=Period (s)

Using the middle value of our last table we can get a power of:

$$P = \left(0,5 \frac{kW}{m^3s}\right) H^2 T = 0,5 * 4,1^2 * 8,6 = 72,28 \frac{kW}{m}$$

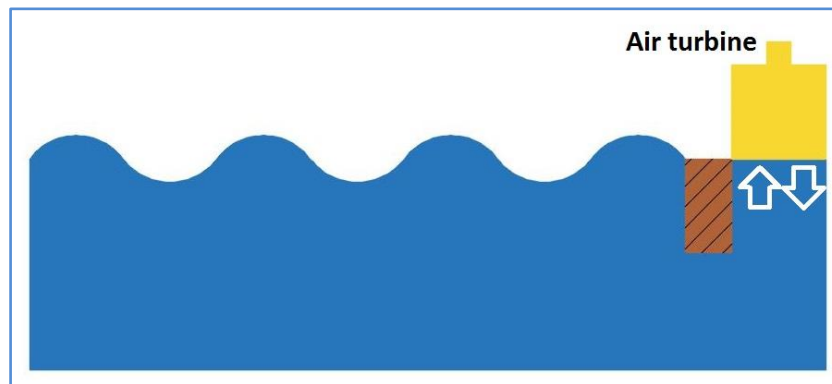


Picture 2: Wave energy map (Source: https://en.wikipedia.org/wiki/Wind_wave)

That is a huge available energy from a renewable source. In other words, using 10km at 45kW/m we can obtain the same power of a thermal power station (about 400MW).

Nowadays there are basically six ways to obtain energy from waves

- I. **Terminator devices:** Usually are built on land, and capture the break energy of the wave, for example moving air inside and outside trough a turbine.



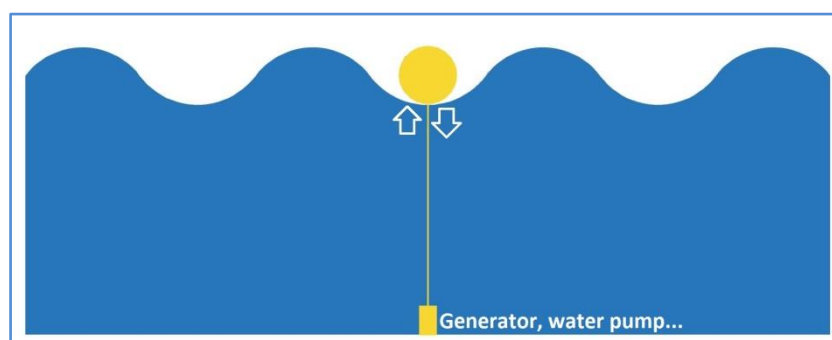
Picture 3: Terminator device

- II. **Attenuators:** Big tubes separated in parts, each union has mechanisms to extract energy on the flexing union. They are mounted in the wave direction.



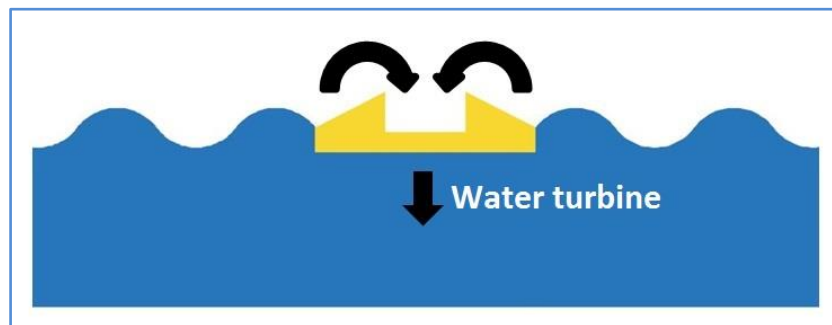
Picture 4: Attenuator device

- III. **Point absorbers:** Like buoys float on the surface, and moves up and down with every wave to get energy. They can be anchored to the sea floor or other base.



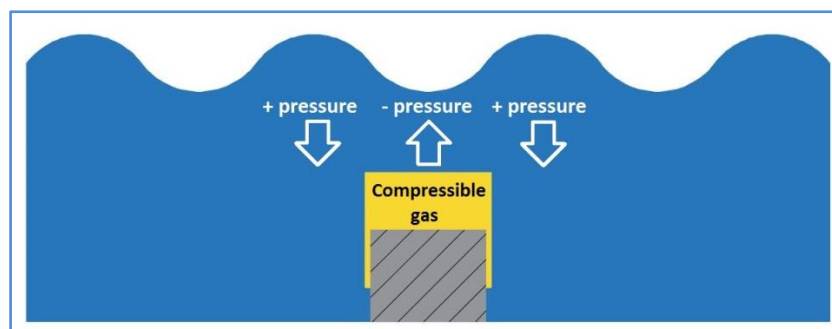
Picture 5: Point absorber device

- IV. **Overtopping devices:** Coast or sea platforms that get the entire wave taking profit of their kinetic and potential energy to create an amount of water that pushes a turbine.



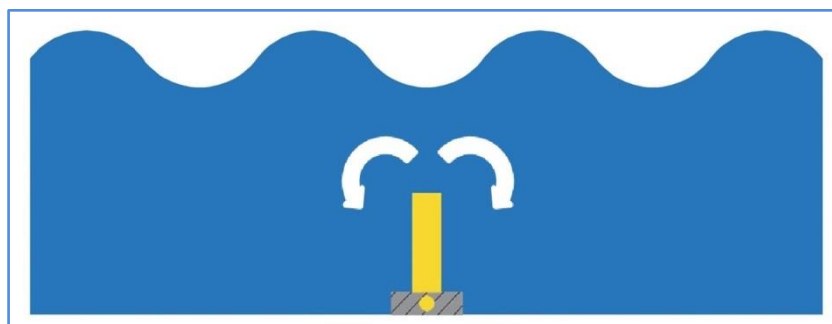
Picture 6: Overtopping device

- V. **Differential pressure:** Use the differential pressure between two points (or the same point at different times) of the wave to move a fluid or drive a generator.



Picture 7: Differential pressure device

- VI. **Oscillator devices:** They take profit of the kinetic movement of the water. They have an oscillating part that moves a generator, usually are placed on the floor.



Picture 8: Oscillator device

1.3 First approach to the project's main concept

The project's idea is to build a simply, reliable, cheap and easy to deploy device but adding the latest technology in the field like a linear generator replacing old mechanical systems to drive a conventional rotary generator.

The goal is to design a very useful device to deploy on areas where the most profitable renewable energy is the wave power, and bring there a cheap device that does not require a high amount of maintenance or expensive projects to get it working.

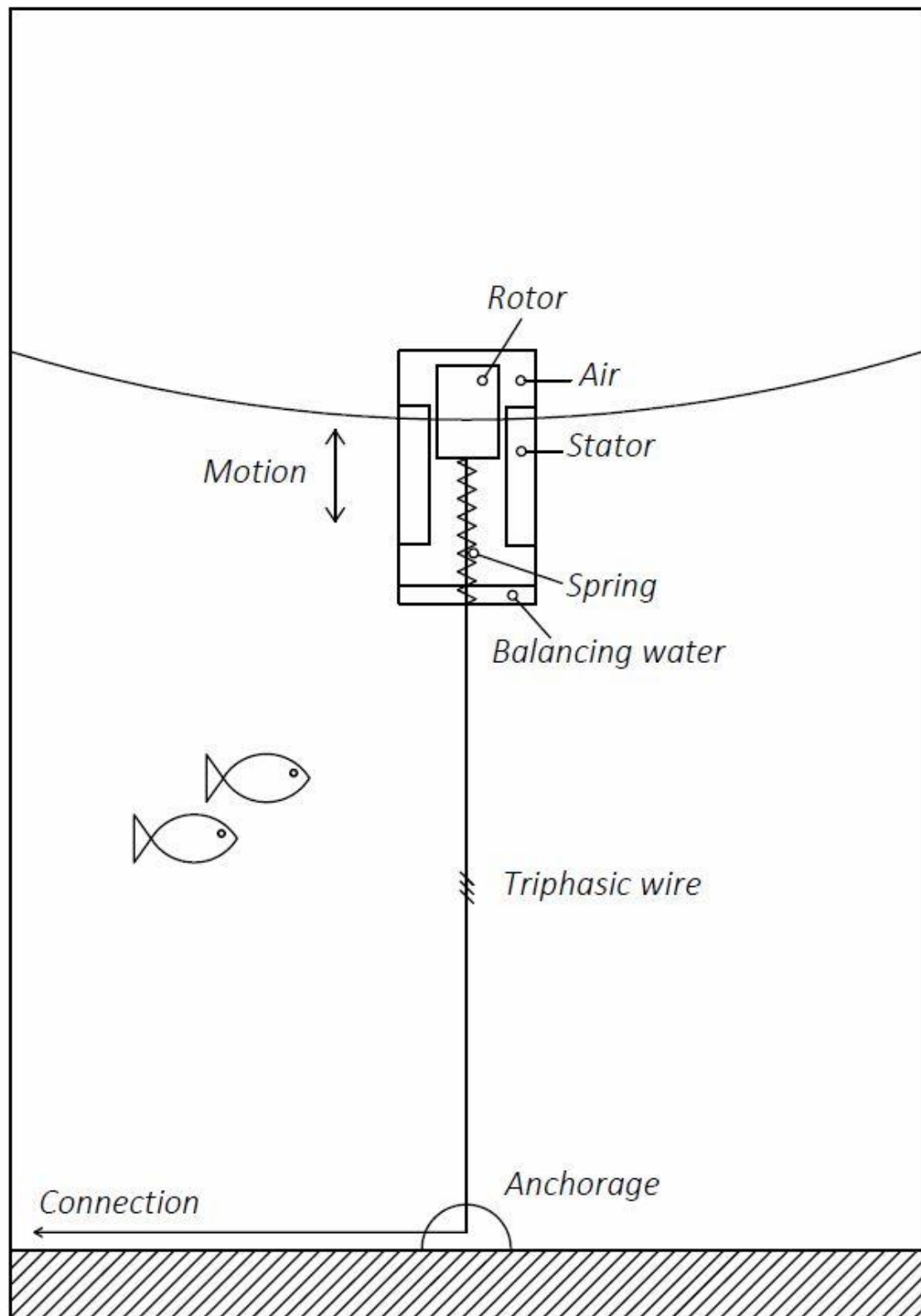
Taking these goals in mind the best suitable systems, for their less complexity and relative high performance, are the point absorbers and differential pressure. But differential pressures ones have some difficulties over the point absorbers, one of them is the impossibility to install on all depths, because the differential pressure under a wave decrease on deep waters, and for that reason they must be designed and deployed in specifically depths. In addition the most attractive differential pressure systems are patented, as the Archimedes wave swing (AWS). On the other hand point absorbers systems can be installed in more environments, are simplest, more reliable, and take profit of the same potential energy of a wave, and so the project will be built on the point absorber base.

The device will be an all in one device that will contain all the elements in a single package it will do all the functions required to transform the wave's energy into electricity. It will contain the floating device, the generator, electronics, protection and signal devices, etc. And will be connected to the electrical grid by a triphasic wire that will work too as a chain anchoring the device to the sea floor and keeping it at place.

As a point absorber device it will take profit of the potential wave's energy, discarding most of the kinetic energy, This will not be a problem because wave power devices are not oriented on the primary source performance (there is a vast energy available), but take care on other fields, as the ones commented before.

The device will be focused on independent work of a single unit, but will be able to work on multiple systems to adapt at bigger projects, making it modular if is necessary.

The device will have a returning system to compensate the wire's weight and keep the wire always on tension and the rotor on their resting position when the device is on the lowest part of the wave.

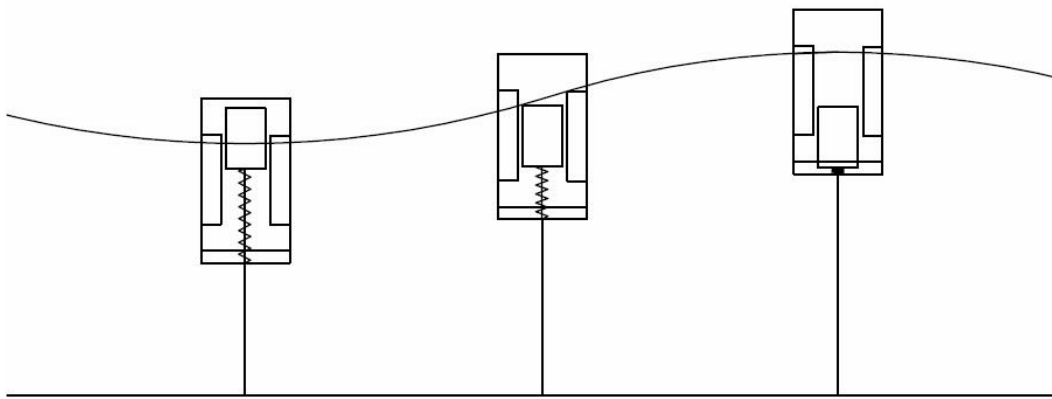


Drawing 1: Project's concept

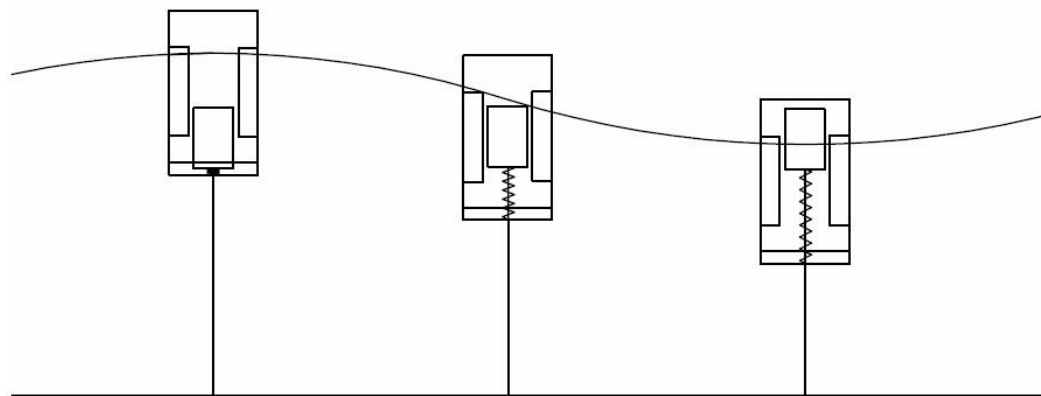
The next pictures show the operation motion of the generator. When the wave raises the generator enclosure rises too meanwhile the rotor keeps in place thanks to the floor attached wire. Since there is a magnetic force between the rotor and the stator a mechanical energy is transferred into electrical energy by the generator.

There are two different operation ways that will be studied furtherly and the best option determined later:

- Generate all the force (and mechanical power) only at the rising stage leaving the generator turned off at falling stage.
- Generate the force (and the mechanical power) distributed on the entire cycle, when rises and when falls. To do it will be necessary a component capable to store half of the rise energy to deploy it when it falls, for example an improved spring, a pneumatic or hydraulic system...



Picture 9: Motion at wave rising



Picture 10: Motion at wave falling

2 Mechanical design

2.1 Starting the design and bases

Calculation and design starts defining the key points:

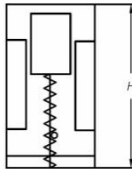
Expected working conditions: (based on the middle value of the table and map)

- Wave height = 3 m
- Wave Period = 6 s
- Wave speed = $\frac{gravity}{4\pi} * period = \frac{9,8}{4\pi} * 6 = 4,68 \frac{m}{s}$
- Wave length = $wave\ speed * period = 4,68 * 6 = 28,08\ m$
- Max wave power = $\left(0,5 \frac{kW}{m^3s}\right) H^2 T = 0,5 * 3^2 * 6 = 27000 \frac{W}{m}$

External device desired dimensions



The device will be built on a cylinder design. For that reason the proportions between diameter and height will be about 1:2 (2m of diameter = 4m of height).



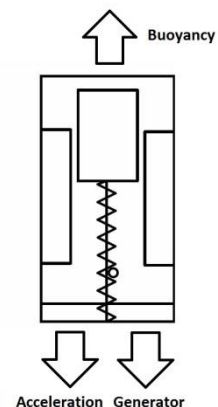
Another design constant is the floating part of the height above the water, it is wanted to be around 1/4 of the height.

For that, floating height will be the diameter/2

Our device will have three primary forces acting on it:

- Buoyancy (+): Performed by the volume floating (diameter * floating height)
- Device acceleration (-): The device mass * acceleration required
- Generator force (-): Force required to produce electricity on generator

(Device's weight will be equilibrated by submerged volume)



Buoyancy and acceleration forces will be directly ruled by device external dimensions, meanwhile generator force will be designed with remaining amount. To choose an optimal external dimension, buoyancy force and power will be compared with acceleration force and power lost, between ranges of 1m to 2m diameter. (2 to 4m usually wave's height)

(For first designing steps on external dimensions, total weight will be approximated to enclosure weight, and to calculate it steel will be supposed as enclosure material, with a thickness of 1cm (rising proportional to diameter rise) for 1m diameter. Air, generator, external devices, wire, etc will be ignored. Acceleration required is calculated as uniformly accelerated linear motion between trough and crest on period/2 time)

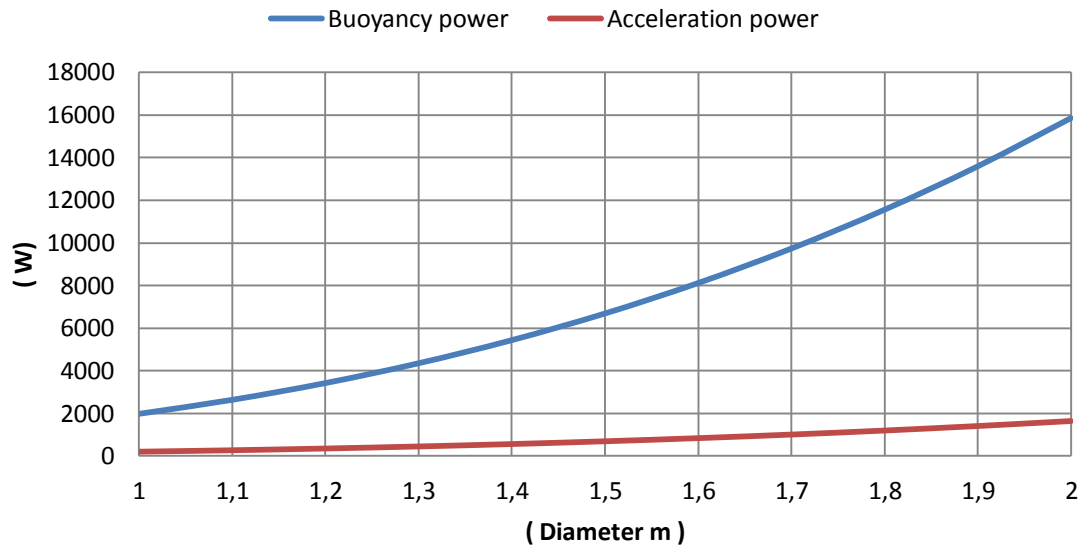
- Calculation of buoyancy force and power:

$$\begin{aligned}
 F &= \text{floating volume} * \text{water density} * \text{gravity} (N) \\
 F &= (\text{top area} * \text{floating height}) * 1030 * 9,8 (N) \\
 F &= \left(\left(\frac{\text{diameter}}{2} \right)^2 * \pi * \frac{\text{diameter}}{2} \right) * 1030 * 9,8 (N) \\
 P &= \frac{\text{Force} * \text{wave height}}{\text{wave period}} = \frac{\text{Force} * 3}{6} (W) \\
 P &= \left(\left(\frac{\text{diameter}}{2} \right)^2 * \pi * \frac{\text{diameter}}{2} \right) * 1030 * 9,8 * 0,5 (W)
 \end{aligned}$$

- Calculation of surface (enclosure) acceleration force and power lost:

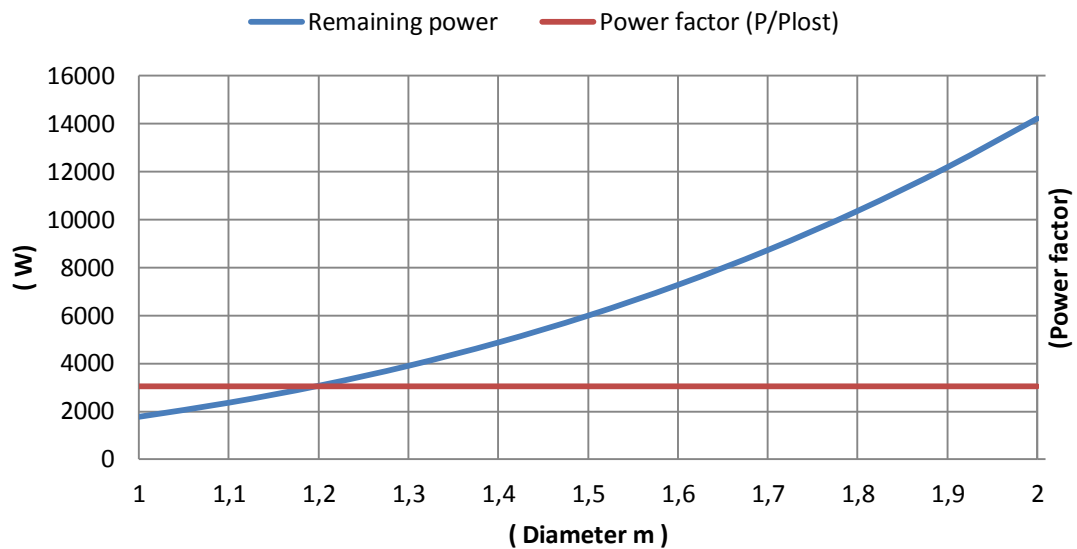
$$\begin{aligned}
 S &= (\text{top area} * 2) + (\text{top perimeter} * \text{height}) (m^2) \\
 S &= \left(\left(\frac{\text{diameter}}{2} \right)^2 * \pi * 2 \right) + \left(2 * \pi * \left(\frac{\text{diameter}}{2} \right) * (\text{diameter} * 2) \right) (m^2) \\
 V &= S * \text{Thickness} * (\text{diameter as thickness rising factor}) (m^3) \\
 M &= \text{Volume} * \text{density} = \text{Volume} * 7850 (kg) \\
 A &= \frac{\text{Wave height}}{0,5 * \left(\frac{\text{period}}{2} \right)^2} = \frac{3}{0,5 * 3^2} = 0,6667 \left(\frac{m}{s^2} \right) \\
 F &= \text{Mass} * \text{acceleration} = \text{Mass} * 0,6667 (N) \\
 P_{lost} &= \frac{\text{Force} * \text{wave height}}{\text{wave period}} = \frac{\text{Force} * 3}{6} (W) \\
 P_{lost} &= S * 0,01 * d * 7850 * 0,6667 * 0,5 (W)
 \end{aligned}$$

Buoyancy power vs acceleration power lost



Statistic 8: Power difference

Remaining power for generation



Statistic 9: Power available

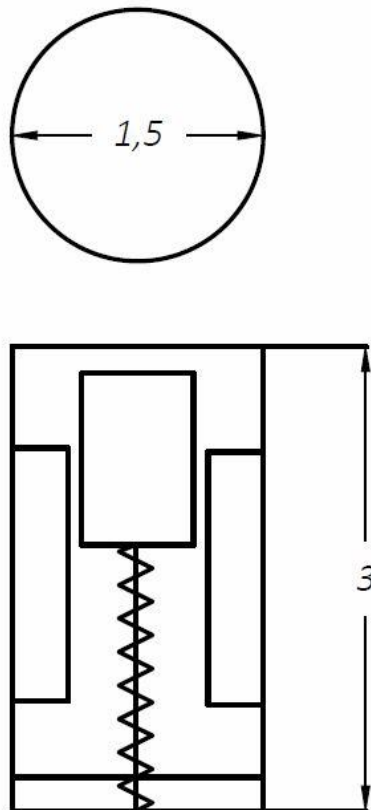
As we can see, the power factor (buoyancy power / acceleration power lost) is constant, and for that all the dimensions are equally efficient. Then the device's diameter and all the enclosure dimensions will be chosen by generator wanted output.

European household electricity consumption is about 3500kWh/year. It means that a house requires an average continuous consumption of 400W. Taking the simplicity and modularity goals in mind a good remaining power for generation would be 6000W of the 1,5 diameter. It means that considering the usual losses and increased weight by ignored parts it is correct to expect a final output generation around 4000W to provide the average energy necessary for 10 European households.

A final necessary calculation step must be done by checking if the underwater part of the device can provide the buoyancy force needed to cancel the device's weight force. The underwater volume is the above water volume * 3 and the weight force is the mass * gravity. It shows correct results of around 40kN of floating force vs 20kN of weight force been able to equilibrate the weight and a remaining extra force to have a margin on next design steps and the parts ignored on weight calculation.

Calculated optimal dimensions:

- Diameter: 1,5m
- Height: 3m



Drawing 2: Calculated optimal dimensions (m)

Electrical conductor cross section: On cross section depends the electrical transportation losses and another important factor, the heat power that wire will need to dissipate. For that is very important to make a good design on the wire to avoid thermal and energy problems. The metal used will be chosen further between cooper and aluminum, but now both of it will be considered as the conductive metal used.

- A triphasic wire without neutral is desired (3 conductors)
- The estimated output generation will be around 4000W
- The maximum wire length to seafloor will be fixed at 200m
- Maximum losses will be fixed to 200W (5% of 4000W)
- Maximum voltage drop will be fixed to 11,5V_{phase} (5% of 230V_{phase})

$$P_{loss} = I_{phase}^2 * R * 3$$

$$I_{phase} = \frac{P}{V_{phase} * 3} = \frac{4000}{230 * 3} = 5,787 \text{ A}$$

$$R_{cu} = \frac{\rho_{cu}}{\left(\frac{S}{l}\right)} = \frac{1,68 * 10^{-8}}{\left(\frac{S}{200}\right)} \quad R_{al} = \frac{\rho_{al}}{\left(\frac{S}{l}\right)} = \frac{2,65 * 10^{-8}}{\left(\frac{S}{200}\right)}$$

$$200 = 5,787^2 * \frac{1,68 * 10^{-8}}{\left(\frac{S}{200}\right)} * 3 \rightarrow S_{cu \text{ min}} = 1,688 \text{ mm}^2$$

$$200 = 5,787^2 * \frac{2,65 * 10^{-8}}{\left(\frac{S}{200}\right)} * 3 \rightarrow S_{al \text{ min}} = 2,662 \text{ mm}^2$$

*Voltage drop is directly proportional to resistance as it is to power, for that reason it is no recalculated and assumed the section values as correct.

Calculated optimal electrical conductors:

- Copper: 3 x 1,688 mm² (minimum) → 3 x 2,5 mm² (normalized IEC section)
- Aluminum: 3 x 2,662 mm² (minimum) → 3 x 4mm² (normalized IEC section)

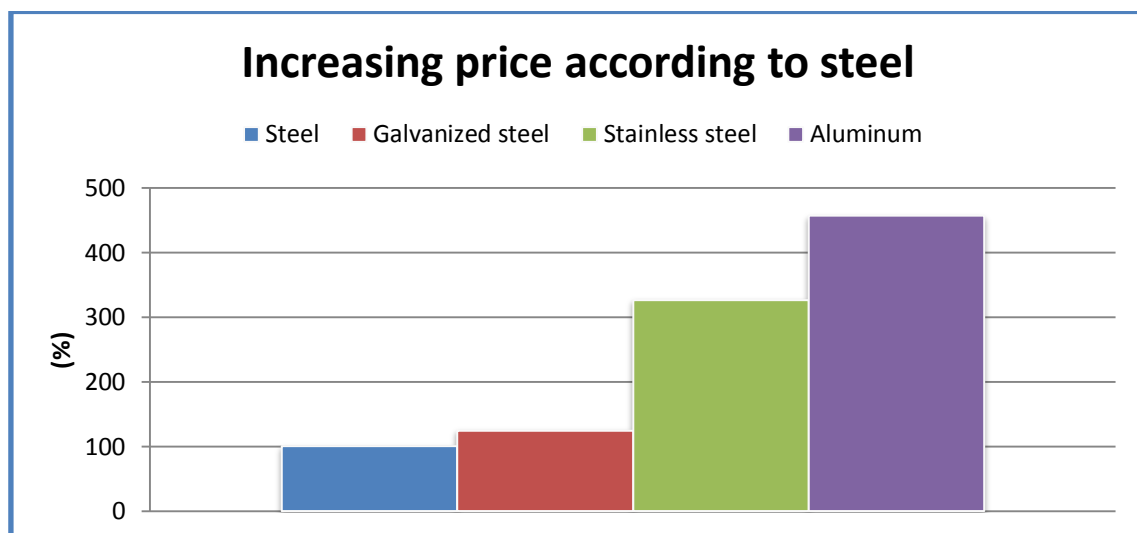
2.2 Choice of best suitable materials

External enclosure: It is the most critical part of the device due the high oxidizing power of the salt water (Saltwater corrodes metal five times faster than fresh water and the ocean air corrodes it ten times faster than land air) and the need of support high water pressures on eventual big waves that can cover it below some meters of water.

There are 4 typical and extended used in marine environments options for the enclosure:

- Steel: typical carbon steel and alloys, specially marine approved ones such AH36, DH36, EH36 or MD, ME, MF or MG. Regular steel price: 0,882€/kg
- Galvanized steel: The zinc coated will be sacrificed on oxidation to protect the steel, especially if heavy coated are applied. Regular galvanized steel: 1,10€/kg
- Stainless steel: Steel alloy with chromium and nickel protecting it to external corrosion, the most suitable to ocean environment is the grade 316 with molybdenum. Regular stainless steel price: 2,88€/kg
- Aluminum: A high resistant metal, there are lot of grades suitable for marine environments like 5052, 5083 or 6061-T6. Regular aluminum price: 4,03€/kg

(Bronze, copper and brass are not considered for the high demanding mechanical proprieties needed)



Statistic 10: Increasing enclosure price

Bearing in mind the economical goal of the design and the big increasing price between regular steel and stainless steel or aluminum and considering the good existing options to prevent corrosion on the steel as:

- Specialized marine zinc paintings
- External epoxy coatings
- Cathodic protection by zinc sacrificial anodes

Finally the enclosure material will be made on standard marine grade steel (AH36, DH36, EH36) and careful protected by avoid the corrosion of ocean environment.

- A maximum price of 1€/kg will be considered by the global enclosure including the steel and the protections.
- A yield point of 365MPa and a density of 7800kg/m³

Electric wire: It must accomplish 3 functions, anchor the device at the sea floor, hold the rotor while the device and the stator rises holding a force equivalent to the generation and the electrical generation transportation. It must be resistant to the sea floor environment, mechanical resistant to traction and a low resistant conductor to avoid losses.

- Electrical transport: There are two typical metals on this propose, copper and aluminum. Copper has a resistivity of $1,68 \cdot 10^{-8} \Omega m$ while aluminum has a resistivity of $2,65 \cdot 10^{-8} \Omega m$ regarding resistivity is linked to volume it means to obtain the same resistivity it is needed 1,58 times more aluminum volume:

$$\frac{\rho_{al}}{\rho_{cu}} = \frac{2,65 \cdot 10^{-8}}{1,68 \cdot 10^{-8}} = 1,58$$

But aluminum (2700kg/m³) is 3,31 times lighter than copper (8940kg/m³):

$$\frac{d_{cu}}{d_{al}} = \frac{8940}{2700} = 3,31$$

It makes an overall best resistivity per weight on aluminum:

$$\frac{\left(\frac{\rho_{al}}{\rho_{cu}}\right)}{\left(\frac{d_{cu}}{d_{al}}\right)} = \frac{1,58}{3,31} = 0,477$$

It means a lower than a half resistivity by the same metal weight, making the aluminum the best suitable material for the electrical transportation, because the most important factors, price (aluminum price/kg is cheaper) and weight are improved.

- Insulation, protection, and mechanical layers: Mechanical proprieties will be done by a steel mesh layer as a best option over price/performance. Insulation would be done by paper or XLPE, regarding the insulation needed will be low (minor than 1kV) XLPE is the best option with a dielectric strength of 21kV/mm. Finally external protection will be made by a high density polyethylene layer.

- Conductors: Aluminum (2700kg/m^3) (4,03€/kg)
- Insulation layer: XLPE (930kg/m^3) (0,75€/kg)
- Mechanical layer: Steel (7850kg/m^3) (0,882€/kg)
- Protection layer: HD polyethylene (950kg/m^3) (0,95€/kg)

Security system: As a dangerous device to be avoided by ships, it must alert of their presence especially on nights. For that reason a light will be added on top of a tube to alert of their presence.

- Tube: Stainless steel 316 (regarding it will not have mechanical restrictions to use another more expensive option) (8000kg/m^3) (2,88€/kg)
- Light: Externally made of methacrylate (regarding is the best option over polycarbonate or glass on mechanical properties) (940kg/m^3) (0,99€/kg)

Seafloor anchorage: Used to retain the device on their position, regarding on price and simplicity a marine concrete based on Portland cement will be used:

- Marine concrete (2400kg/m^3) (0,03€/kg)

Returning system: Based on a simple spring will keep the wire on tension and the rotor in the resting position when no force upwards is applicate to the device.

- Regular steel (250MPa) (7850kg/m^3) (0,882€/kg)

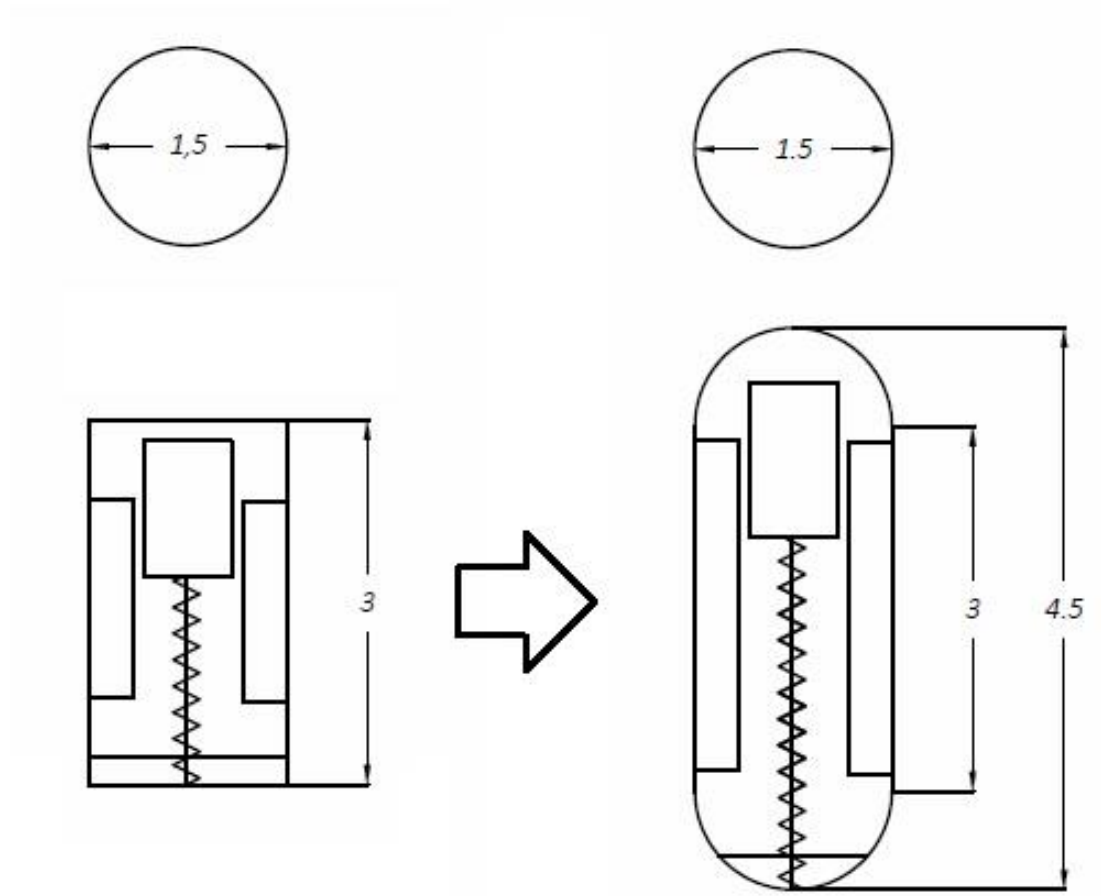
Seals: Used to seal joints and moving parts. Synthetic rubber will be used over natural rubber for specs and durability:

- Nitrile rubber will be used thanks to the good specs of this material on hard environments. (Price and weight will be ignored).

2.3 Final mechanical design and dimensions

Final enclosure dimensions: A shape change will be made on the enclosure caps to leave more available space for the rotor to get a full travel motion on the entire wave travel as well leaving a gap to work on some higher waves than 3m. Another reason to redesign the caps is to improve the mechanical properties of the device.

The caps will be changed from a circular shape to sphere:



Drawing 3: Final external enclosure dimensions (m)

With the shape modification the device gets 1,5 extra meters for the rotor motion and a mechanical improvement on caps reducing the momentum on center and redistributing along the surface.

Next step it is to calculate the thickness of the enclosure's steel (supposed as 1,5cm on previous approximations), it will be calculated to resist a hypothetical 50m height wave:

- A perfectly distributed pressure will be considered
- Linear pressure as 1bar=100000Pa=10m depth
- Approximation by pressure without moments on the device (as a perfect sphere)
- Relative pressure considered regarding inside pressure as atmospheric
- A security factor of 2

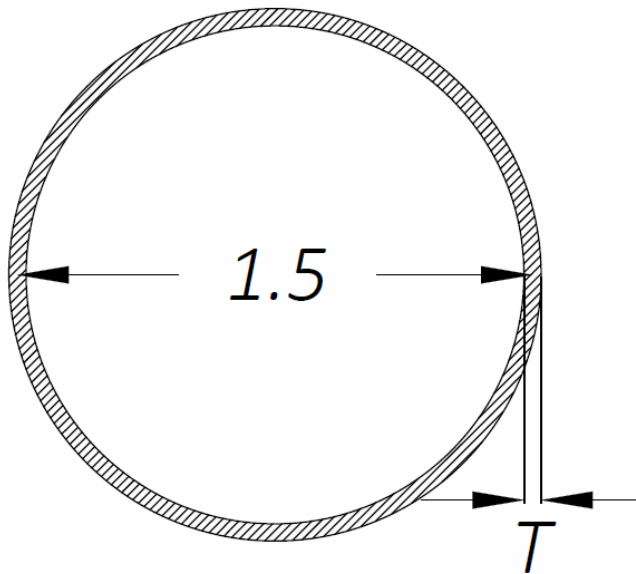
$$Device\ surface = caps_{surface} * 2 + body_{surface} = sphere_{surface} + cilinder_{surface}$$

$$Device\ surface = 4\pi * r^2 + 2\pi * r * h = 4\pi * 0,75^2 + 2\pi * 0,75 * 3 = 21,2058\ m^2$$

$$Device\ pressure\ supported = depht * pressure_{rise} = 50 * 0,1 = 5\ Bar = 500000\ Pa$$

$$Compressive\ force\ supported = pressure * surf. = 500000 * 21,2058 = 10602900\ N$$

Marine steel (used steel on device's enclosure) has a yield point 365MPa and considering a central cut 2D of the device we can increase or decrease the area holding the pressure and consequently calculating the steel's pressure below the yield point:



Drawing 4: Central device's cut (m)

$$\text{Maximum steel pressure} = \frac{\text{Yield point}}{2} = \frac{365000000}{2} = 182500000 \text{ Pa}$$

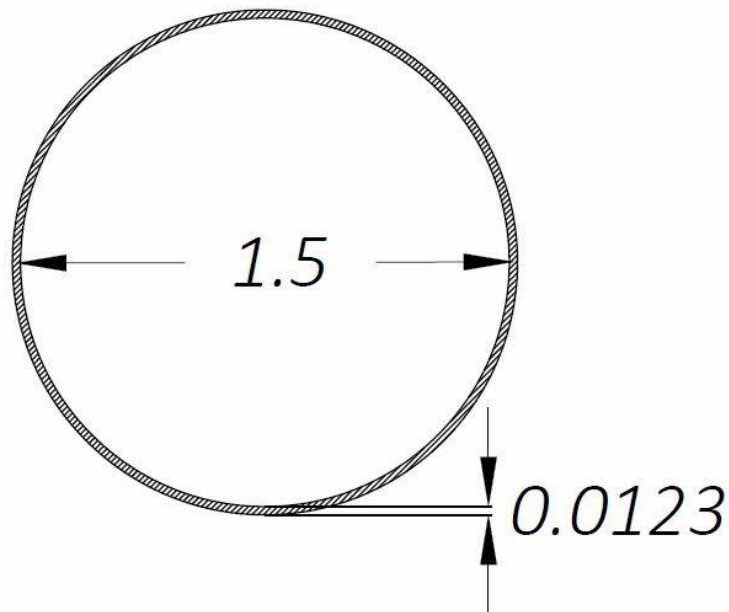
$$\text{Device cut area} = \text{external}_{\text{area}} - \text{inner}_{\text{area}} = \left(\pi * \left(0,75 + \frac{T}{2} \right)^2 \right) - \left(\pi * \left(0,75 - \frac{T}{2} \right)^2 \right)$$

$$\text{Device steel pressure} = \frac{\text{Device's force}}{\text{Device cut area}} = \frac{10602900}{\left(\pi * \left(0,75 + \frac{T}{2} \right)^2 \right) - \left(\pi * \left(0,75 - \frac{T}{2} \right)^2 \right)}$$

$$\text{Device steel pressure} = \text{Maximum steel pressure}$$

$$182500000 = \frac{10602900}{\left(\pi * \left(0,75 + \frac{T}{2} \right)^2 \right) - \left(\pi * \left(0,75 - \frac{T}{2} \right)^2 \right)} \rightarrow \text{Thickness} = 0,01233 \text{ m}$$

So, to resist with security waves up to 50m the device needs a thickness of 1,23 cm



Drawing 5: Final thickness (m)

Once the final enclosure shape is finally defined and thickness is determined a final calculation on enclosure can be done:

- $Enclosure_{surface} = 4\pi * r^2 + 2\pi * r * h = 4\pi * 0,75^2 + 2\pi * 0,75 * 3 = 21,21 \text{ m}^2$
- $Enclosure_{volume} = surface * thickness = 21,2058 * 0,01233 = 0,2614 \text{ m}^3$
- $Enclosure_{mass} = volume * density = 0,2614 * 7800 = 2039,45 \text{ kg}$
- $Enclosure_{price} = mass * price = 2039,45 * 1,00 = 2039,45 \text{ €}$
- $Enclosure_{weight} = mass * gravity = 2039,45 * 9,8 = 19986,58 \text{ N}$
- $Enclosure_{acceleration_{needed}} = \frac{Wave \text{ height}}{0,5 * \left(\frac{period}{2}\right)^2} = \frac{3}{0,5 * 3^2} = 0,6667 \left(\frac{m}{s^2}\right)$
- $Enclosure_{acceleration_{force}} = mass * acceleration_{needed} = 2039,45 * 0,6667 = 1359,70 \text{ N}$
- $Enclosure_{acceleration_{power \text{ lost}}} = \frac{Force * wave \text{ height}}{wave \text{ period}} = \frac{1359,70 * 3}{6} = 679,85 \text{ W}$

And calculations regarding buoyancy and gross obtainable power with this enclosure can be recalculated too:

- $Buoyancy_{force} = floating \text{ volume} * water \text{ density} * gravity \text{ (N)}$
- $Floating \text{ volume} = \frac{sphere_{vol}}{2} + top \text{ area} * floating \text{ height (m}^3\text{)}$
- $Floating \text{ volume} = \left(\frac{4}{3}\pi * 0,75^3 * 0,5\right) + (\pi * 0,75^2) * \frac{1,5}{2} = 2,209 \text{ m}^3$
- $Buoyancy_{force} = 2,209 * 1030 * 9,8 = 22296,96 \text{ N}$
- $Buoyancy_{gross \text{ power}} = \frac{Force * wave \text{ height}}{wave \text{ period}} = \frac{22296,96 * 3}{6} = 11148,48 \text{ W}$

Expected generator output: will be reconsidered too as the gross power rises with the volume gain on the device the expected generation output will be increased too at a range of 8000-4000W setting 6000W as desired output generation on standard working conditions. The wire's sections remains unchanged thanks to the margin on the design being capable to support less than 5% losses on 6000W generation:

$$P_{loss} = I_{phase}^2 * R * 3$$

$$P_{loss \ 5\%} = 6000 * 0,05 = 300 \text{ W}$$

$$I_{phase} = \frac{P}{V_{phase} * 3} = \frac{6000}{230 * 3} = 8,696 \text{ A}$$

$$R_{al} = \frac{\rho_{al}}{\left(\frac{S}{l}\right)} = \frac{2,65 * 10^{-8}}{\left(\frac{S}{200}\right)}$$

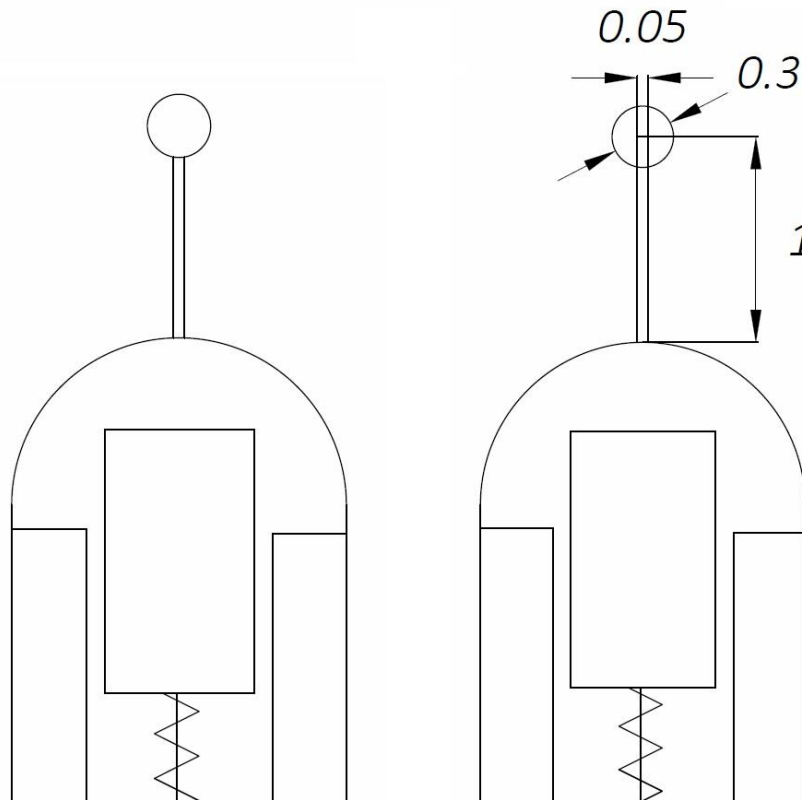
$$300 = 8,696^2 * \frac{2,65 * 10^{-8}}{\left(\frac{S}{200}\right)} * 3 \rightarrow S_{al\ min} = 4\ mm^2$$

We find a value of 4 mm² cross section wire for the max 200m wire length to reach a maximum 5% losses on transport validating the use the same calculated conductor.

Final generation specs:

- Wire's section needed = 4 mm²
- Expected generation output = 6000 W
- Expected generation output range = 4000 to 8000 W
- Maximum losses on transportation over standard conditions = 300 W (5%)

Security system design: Based on a high output LED inside of a transparent enclosure over a stainless steel tube to rise up it, dimensions:



Drawing 6: Security light dimensions (m)

Tube weight (1cm wall thickness):

$$\begin{aligned}Tube_{volume} &= total_{vol} - hole_{vol} = h * \pi * r_{ext}^2 - h * \pi * r_{int}^2 \\Tube_{volume} &= 1 * \pi * 0,025^2 - 1 * \pi * 0,015^2 = 0,001257 \text{ m}^3 \\Tube_{mass} &= Volume * density = 0,001257 * 8000 = 10,05 \text{ kg} \\Tube_{weight} &= mass * gravity = 10,05 * 9,8 = 98,52 \text{ N} \\Tube_{price} &= mass * price = 10,05 * 2,88 = 28,94 \text{ €}\end{aligned}$$

Light enclosure (2,5cm wall thickness):

$$\begin{aligned}Light_{volume} &= total_{vol} - empty_{vol} = (\frac{4}{3} * \pi * r_{ext}^3) - (\frac{4}{3} * \pi * r_{int}^3) \\Light_{volume} &= (\frac{4}{3} * \pi * 0,15^3) - (\frac{4}{3} * \pi * 0,125^3) = 0,005956 \text{ m}^3 \\Light_{mass} &= Volume * density = 0,005956 * 940 = 5,599 \text{ kg} \\Light_{weight} &= mass * gravity = 5,599 * 9,8 = 54,87 \text{ N} \\Light_{price} &= mass * price + 3 * LED_{SMD 100W} \\Light_{price} &= 5,599 * 0,99 + 3 * 30 = 95,54 \text{ €}\end{aligned}$$

- *Security system mass* = 10,05 + 5,599 = 15,649 kg
- *Security system weight* = 98,52 + 54,87 = 153,39 N
- *Security system price* = 124,48 €

Final wire dimensions: starts on 3 aluminum conductors 4mm^2 sections calculated on the previous chapter (2.1) which means 3 conductors of 2,257mm diameter separated 1mm each of them and another 1mm to steel mesh by an 8mm diameter XLPE layer.

The steel mesh will be calculated to support the maximum buoyancy force at security factor of 2. It means a force of:

$$F = \text{floating volume} * \text{water density} * \text{gravity} (N)$$

$$F = \left(\left(\frac{4}{3} \pi * 0,75^3 * 0,5 \right) + (\pi * 0,75^2) * \frac{1,5}{2} \right) * 1030 * 9,8 (N)$$

$$F = 2,209 * 1030 * 9,8 = 22296,96 N$$

So the steel layer must resist 44593,92N. As regular steel has yield strength of 250MPa the wire will need a steel layer of:

$$Pa = \frac{N}{m^2}$$

$$250 * 10^6 = 44593,92 \frac{N}{m^2} \rightarrow 0,0001784 m^2$$

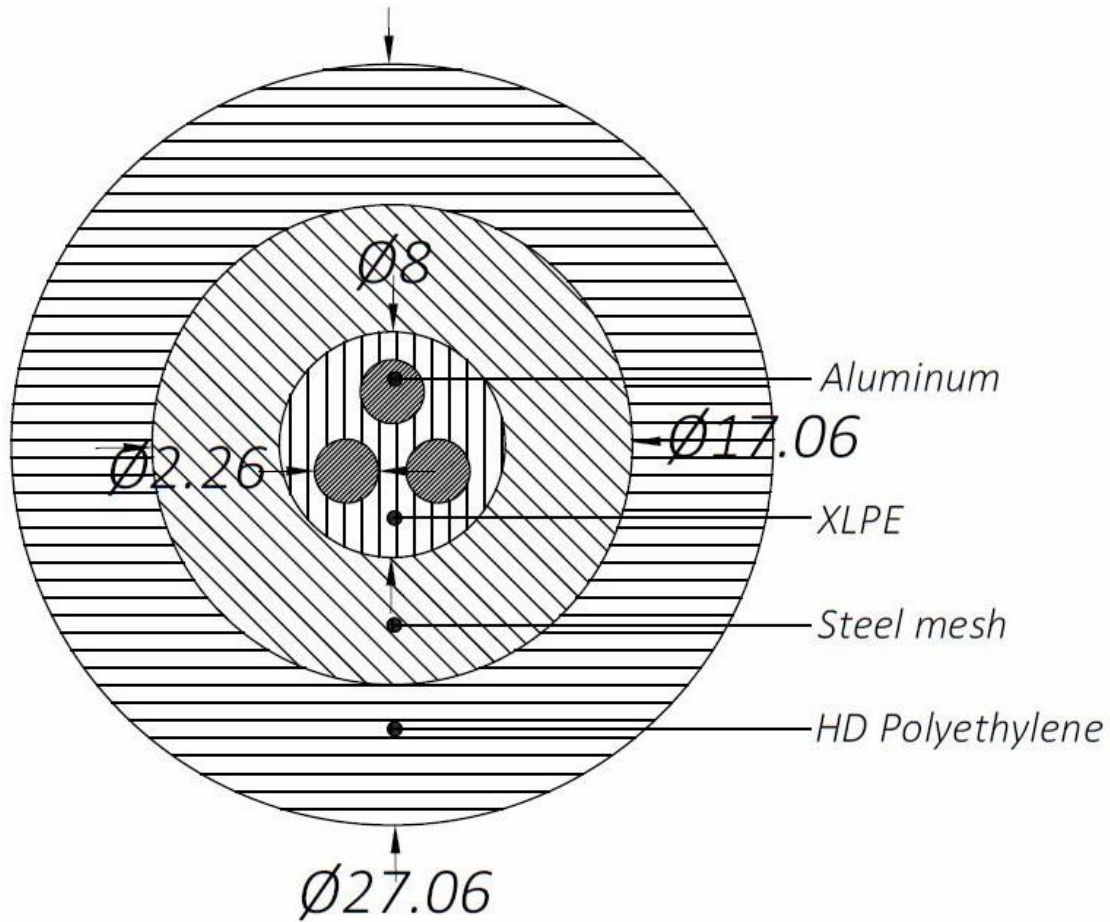
In consequence the steel mesh layer must have an area of 178,38mm² and regarding it holds inside the XLPE layer of 8mm diameter the steel layer diameter must be:

$$Area = r^2 * \pi$$

$$Steel_{area} = 178,38 = Absolute_{area} - XLPE_{area} = r^2 * \pi - 4^2 * \pi$$

$$Steel_{radius} = \sqrt{\frac{178,38 + 4^2 * \pi}{\pi}} = 8,531 mm$$

A steel layer of 17,06 mm diameter is required. Finally a 5mm thickness layer of high density polyethylene will be added for external protection.



Drawing 7: Final wire design (mm)

$$Weight = Layer_{area} * 1m * (Layer_{density} - water_{density}) * gravity \left(\frac{N}{m} \right)$$

$$Aluminum_{weight} = (4 * 10^{-6} * 3) * 1 * (2700 - 1030) * 9,8 = 0,1964 \frac{N}{m}$$

$$XLPE_{weight} = ((4 * 10^{-3})^2 * \pi - (4 * 10^{-6} * 3)) * 1 * (930 - 1030) * 9,8 = -0,0375 \frac{N}{m}$$

$$Steel_{weight} = (178,38 * 10^{-6}) * 1 * (7850 - 1030) * 9,8 = 11,92 \frac{N}{m}$$

$$Polyethylene = (((13,53 * 10^{-3})^2 * \pi) - 178,38 * 10^{-6}) * 1 * (950 - 1030) * 9,8 = -0,3110 \frac{N}{m}$$

- Wire's weight / meter = 11,77 N/m
- Wire's max weight (200m) = 2353,58 N (5,28% of wire's strength)

$$Price = Layer_{area} * 1m * density * price \left(\frac{€}{m} \right)$$

$$Aluminum = (4 * 10^{-6} * 3) * 1 * 2700 * 4,03 = 0,1306 \frac{\text{€}}{\text{m}}$$

$$XLPE = ((4 * 10^{-3})^2 * \pi - (4 * 10^{-6} * 3)) * 1 * 930 * 0,75 = 0,0267 \frac{\text{€}}{\text{m}}$$

$$Steel = (178,38 * 10^{-6}) * 1 * (7850) * 0,882 = 1,235 \frac{\text{€}}{\text{m}}$$

$$Polyethylene = (((13,53 * 10^{-3})^2 * \pi) - 178,38 * 10^{-6}) * 1 * 950 * 0,95 \\ = 0,3580 \frac{\text{€}}{\text{m}}$$

- Wire's price / meter = 1,750 €/m
- Wire's max price (200m) = 350,06 €

Returning system: it is based on a regular steel spring with a greater force than wire's weight to keep it always on tension and the rotor in the correct resting position.

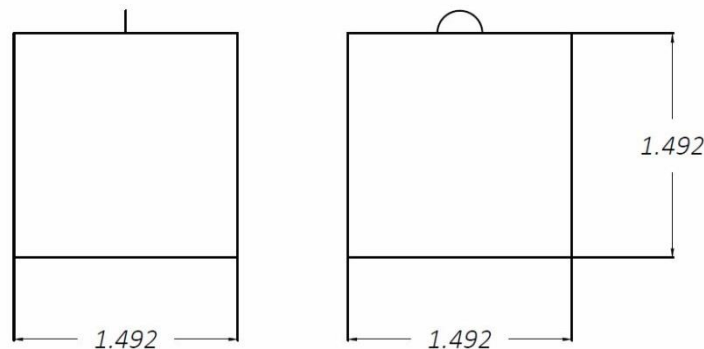
$$Spring_{minimum\ force} = Wire_{max\ weight} = 2353,58\ N$$

So a spring of 3000 N will be added to ensure the good operation of the device.

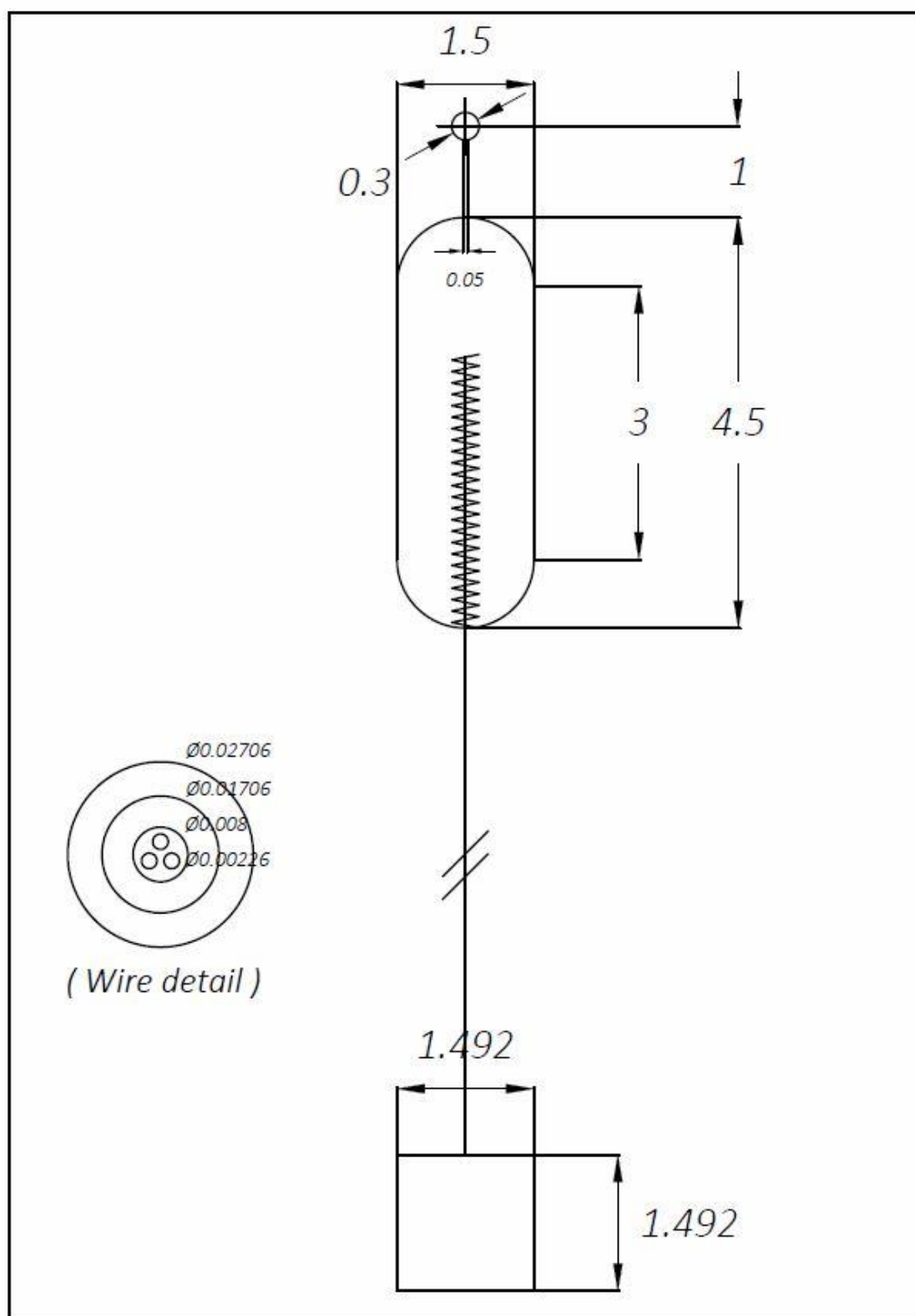
- Spring's force (seeking linearity on travel) = 3000 N
- Spring's approximated mass and weight = 35kg and 343N
- Spring's approximated price = $35kg * 0,882 \frac{\text{€}}{kg} = 30,87\ \text{€}$

Seafloor anchorage: Based on a buried block of marine concrete to hold the device in a fixed position. It must support the wire's maximum strength (44593,92N):

- Anchorage mass and weight = 4550,40kg and 44593,92N
- Anchorage price = $4550,40kg * 0,03 \frac{\text{€}}{kg} = 136,51\ \text{€}$
- Anchorage cube volume = $\frac{mass}{density} = \frac{4550,40}{(2400-1030)} = 3,321\ m^3$



Drawing 8: Anchorage dimensions (m)



Drawing 9: Device final mechanical dimensions (m)

3 Electrical design

3.1 Introduction to reluctance linear generators

A regular synchronous generator works inducing electricity in the stator's wire turns by the rotor's magnetic field. As rotor is in motion the magnetic field is in motion too and it is continuously crossing the stator wires inducing on it the electrical potential based on the following equation:

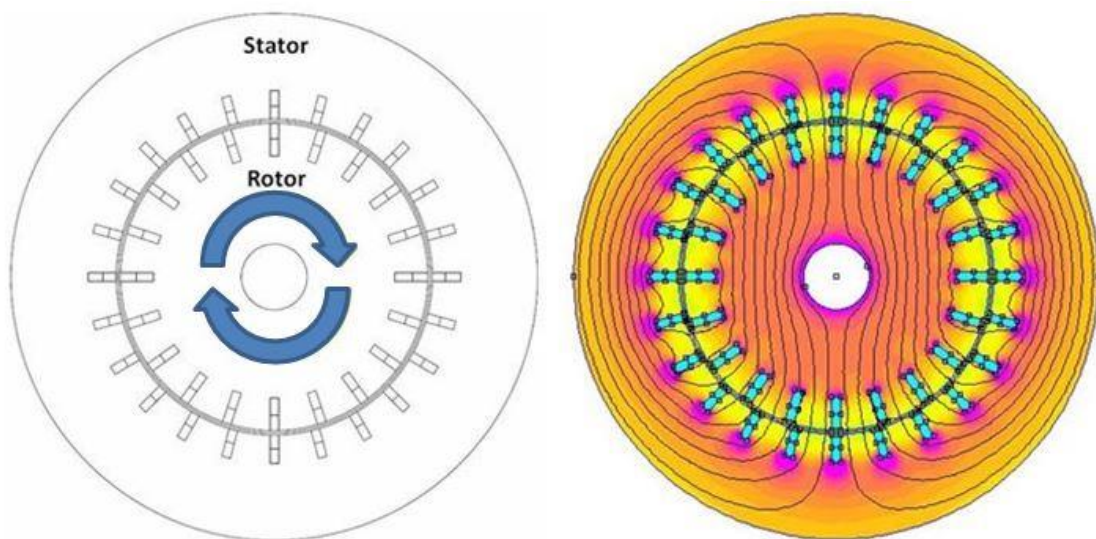
$$e = (\vec{v} \times \vec{B}) * lenght$$

- e = Electrical induced potential in the conductor (V)
- v = Speed of magnetic field versus conductor (m/s)
- B = Induction value (T)

On the entire generator conductors and regarding total electrical potential induced we can use the following equation to calculate an approximation based on sinusoidal flux:

$$E = 4,44 * f * N * \hat{\phi}$$

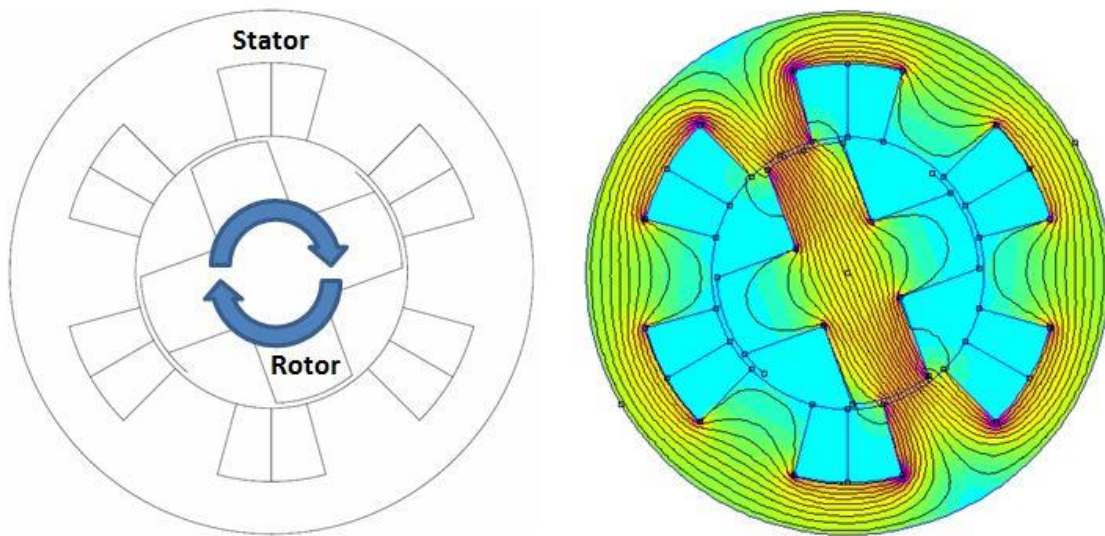
- f = frequency (hz)
- N = Conductor turns
- Φ = Maximum magnetic flux (Wb)



Picture 11: Synchronous regular generator drawing and magnetic flux rendering

On a reluctance generator the electrical potential is not induced by rotor's magnetic field on the conductors. Now the stator conductors are electrical powered generating the magnetic field that will cross the rotor and the rotor will be a simple magnetic conductor but depending on the rotor position the magnetic conductivity will change.

When the rotor is crossed by the magnetic field and an external force turns the rotor on a more difficult magnetic flux flow if the external force is maintained constant, by the conservative energy law, the magnetic energy lost will be transferred in an electrical energy rise, and this is the working principle of a reluctance generator.



Picture 12: Reluctance generator drawing and magnetic flux rendering

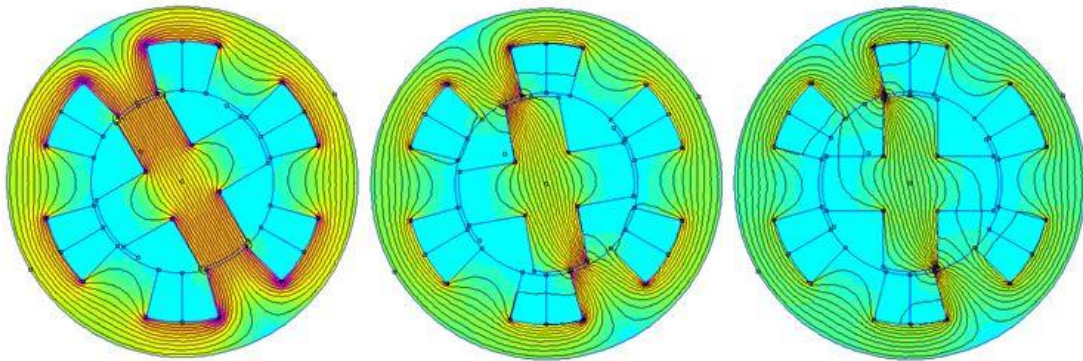
$$Total_{energy} = Electric_{energy} + Magnetic_{energy} + Mechanic_{energy} (J)$$

- $Electric_{energy} = U * I$
- $Magnetic_{energy} = \frac{1}{2} * \phi * I = \frac{1}{2} * L * I^2$
- $Mechanic_{energy} = F * distance$

When mechanical energy is constant, if magnetic energy lows, to maintain the total energy balance the electrical energy must grow, so electrical energy production is directly proportional to the magnetic energy lost as follows:

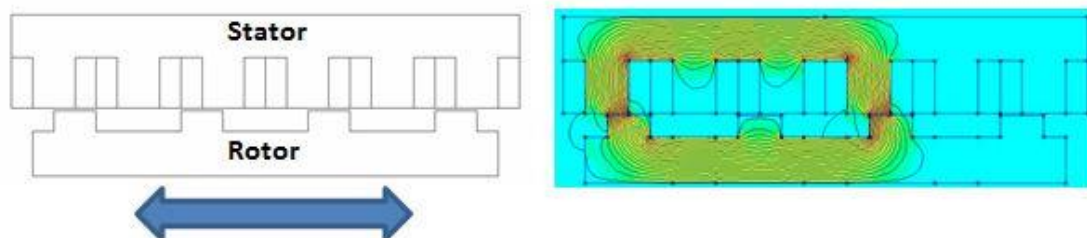
$$\Delta Electric_{energy} = -\Delta Magnetic_{energy}$$

In the next rotor sequence it is possible to see how magnetic field changes with the rotor position and consequently how the magnetic energy is transferred to electrical energy:



Picture 13: As the reluctance increases the magnetic field decreases and the electrical energy rises

Finally, **on a lineal reluctance generator** the same principles of a rotatory reluctance generator are used, but in a linear way. The easiest way to understand it is thinking on it like the stator is spread out and the rotor too, aligning or misaligning with the stator teeth phases by moving around the X axis, not in a rotatory way.



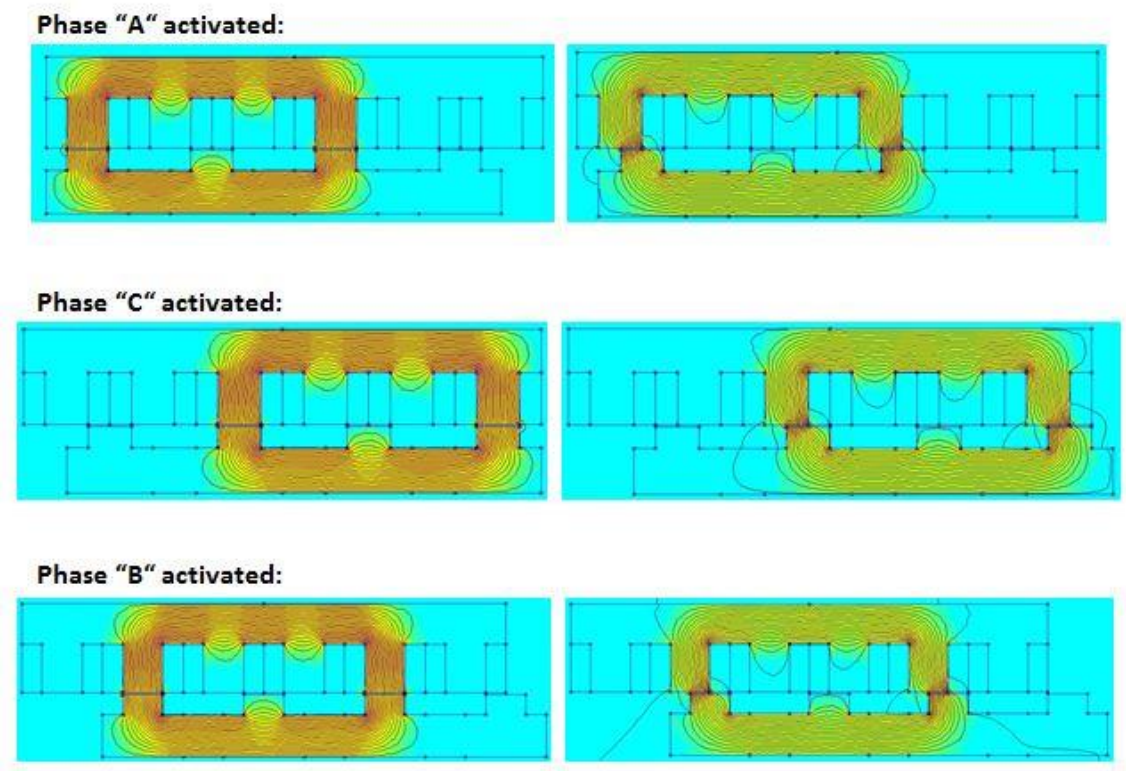
Picture 14: Linear reluctance generator drawing and magnetic flux rendering (phase A activated)

It allows building a generator that can take profit of a linear motion without any device to convert it on a rotatory motion. But it has some disadvantages, the most important one is that effectiveness on the way of electrical energy by generator volume is lower than a rotatory generator so it means a bigger generator and a bigger enclosure, but on the other hand it provides a more reliable generator than a rotatory generator with an external device transforming the linear motion into rotatory.

A linear reluctance generator requires an electronic driver to commute the active phase between the phases on the stator. In this example the stator has 3 phases (A, B, C) and the driver must change from one to other at the targeted point where the

phase is doing a restrictive force over the rotor and is starting to change to a positive force on it acting like a motor, at this point the phase must change to restart the phase cycle restricting the rotor motion to generate electrical energy with the loss of magnetic energy. To archive it the rotor must be unbalanced on teeth number with the stator to provide a switch point between phases.

On the next sequence it is showed how the linear generator works on an entire cycle, the principle is the same of the rotatory reluctance generator, it generates electrical energy with the magnetic energy loss when the reluctance increases.



Picture 15: Cycle of the linear reluctance generator, showing the phase changes

As the rotor moves to the right from one phase to another is restricting the magnetic flux and decreasing the magnetic energy converting it on electrical energy to maintain constant the total energy of the system.



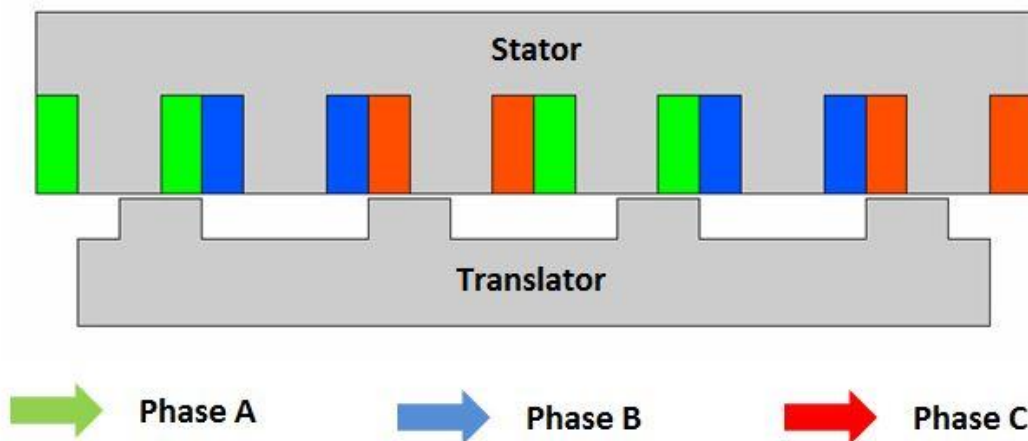
3.2 Generator magnetic and electrical design

Generator design starting specs:

- **Generator type** = Linear switched reluctance
- **Expected power output** = Around 4000 to 8000W → 6000W standard
- **Force needed on the translator (previously named rotor)** = 12000N on a single up cycle or 6000N on an up and down cycle with the force distributed on each.
- **Design space for the generator** = cylindrical 1,2m*3m (15cm enclosure margin)
- **Stator and translator material** = Electrical steel (not oriented grain)
- **Conductors material** = Annealed copper ($\rho=1,72 \cdot 10^{-8}$)

Regardless on price copper and electrical steel will be used on the generator because on this device area the power generation density and weight are mandatory. The previously calculated force remaining for generation will be used, with a margin of 8000W to 4000W on standard condition and 6000W as standard over magnetic, electric, thermic and performance calculations, but being capable to adapt at sporadic environment changes.

As the generation will be done over a triphasic line, the generator will be built on a 6:4 configuration, it means 4 translator teeth by 6 stator teeth, that allows to have a 3 phase configuration on the generator because every phase takes 2 teeth for the magnetic flux, additionally a regular proved and reliable 50% stator tooth width and 50% coil width will be used to ensure good mechanical properties and dimensions.



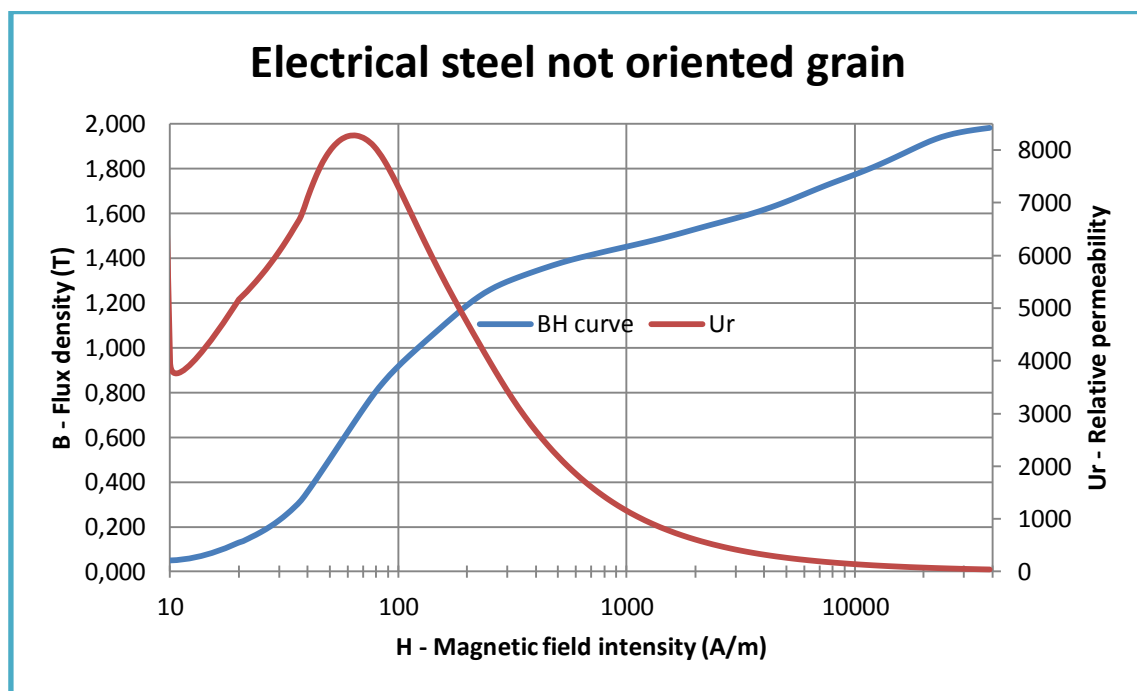
Picture 16: Generator teeth configuration

The generator will work on DC supply to avoid losses on the steel, coils and allow a more current density on conductors, so later an inverter will be used with the controller to adjust the power generated to the power grid.

Prior to start the generator design it is mandatory to determinate an optimal flux density on the stator and the rotor (made on electric steel). The magnetic flux density must be enough to exploit at maximum the magnetic steel used on the generator without saturating it so much that could become so magnetically restrictive to decrease the generator performance. In essence the more saturation on the steel, the more current is needed to increase the same level of magnetic flux. For that reason a higher saturation increases the losses on the copper to create the magnetic flux, but a higher saturation in the steel decreases the volume and the weight of the generator.

- High saturation: low generator volume and weight, high losses.
- Low saturation: High generator volume and weight, low losses.

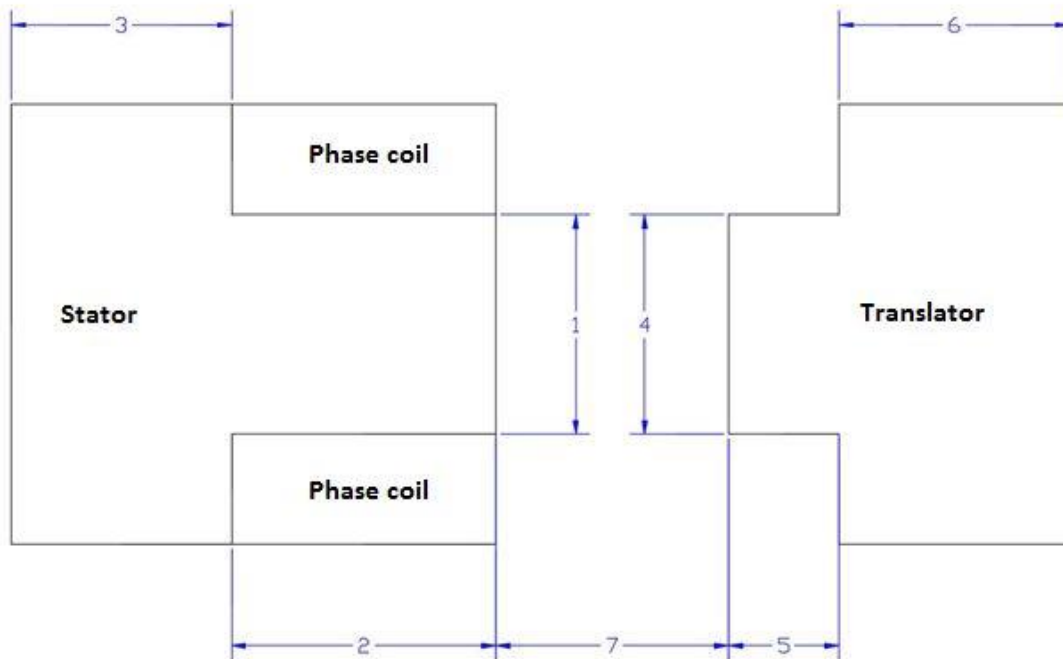
So, it is a key point set an optimal magnetic density on the generator to get the best Performance by volume device.



Statistic 11: Electrical steel specs

As the generator volume and specifically the generator's weight is a critical part of the design a high magnetic density will be pursued to reduce the weight and improve the generation/volume on performance detriment. Between 1,5T to 1,7T will be the density target on the stator and translator teeth.

The generator design starts at the most important point of the entire generation system, the stator and the translator teeth, it will determine the magnetic flux and how it will variate over the motion of a cycle and consequently how much energy will be transferred from magnetic to electric energy thanks to the mechanical force done on the translator.



Drawing 10: Stator and translator teeth dimensions

1 → Stator tooth width: It is a generator constant, it will not affect directly on performance because all other dimensions are proportional to it. Less width means more teeth and more width less teeth. Will be determined by mechanical desired properties.

2 → Phase coil height: As width is determined by tooth width / 2 the height of the slot for the coil wires will be determined by calculation, seeking the desired flux density on the electrical steel and for that actuating over the coil only adjustable dimension, the height until the desired flux density is reached. The copper wires will be rounded and enameled for that reason a filling constant of 0,6 will be used.

3 → Stator yoke height: To ensure the same magnetically flux density over the magnetic circuit identical tooth width dimensions will be used on the yoke height.

4 → Translator tooth width: As the same stator yoke reason and to ensure not overlapping the magnetic flux over different phases the translator tooth width will be the same of the stator tooth width.

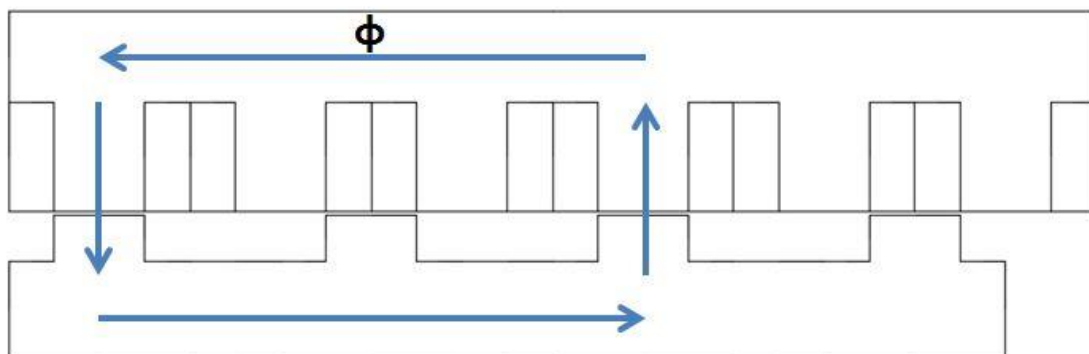
5 → Translator tooth height: That is an important dimension as it determinates a considerable difference between the aligned and unaligned reluctance because the aligned air gap and the unaligned air gap affect as a fundamental way on the reluctance variation. A desirable rate of 1:5 reluctance from aligned to unaligned position is pursued.

6 → Translator yoke height: will be, as the stator yoke, with the same dimensions of the tooth width to ensure the same magnetically density flux over the circuit.

7 → Air gap between teeth: The air has extremely low permeability, for that reason is important to reduce the air gap on aligned position to the maximum. By nowadays production technology it is common to use a regular 1mm air gap between teeth.

***Yoke's adjustment:** As the generator will be built in a cylindrical way and on drawings only appears a cut of it, the depth dimension cannot be appreciate and is a critical part over the reluctance. For that reason a scale over the yoke's dimensions will be done to ensure that has the same flux cross section even if they are on different radius position taking as pattern the radius on the air gap. For example, if the stator yoke's is at 400mm position and the air gap is on 300mm a reduction of $(300/400) \times \text{yoke's height}$ will be made to ensure the same flux cross section and reduce the volume and weight at the maximum possible.

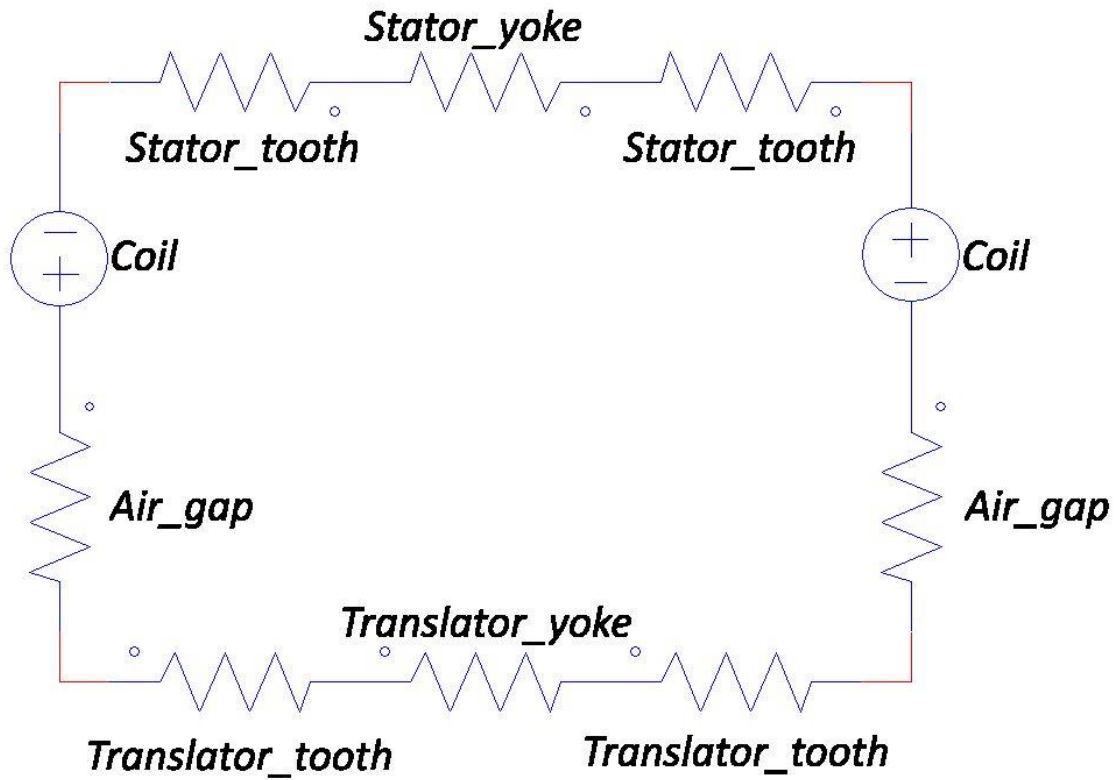
The magnetic circuit and reluctance must be considered for the teeth dimensions:



Drawing 11: Phase flux schema

The magnetically circuit is a representation of the magnetically properties like an electrical circuit, taking as source, intensity and resistance the magnetic parameters:

- $U = I * R \rightarrow Fm = \phi * Rm$
- $Fm = N * I (A)$
- $\phi = L * I (Wb)$
- $Rm = \frac{1}{\mu} * \frac{l}{s} (\frac{1}{H})$



Picture 17: Magnetic circuit

4 different assays over 2 different tooth configuration and winding solutions will be tested on 2 different radius position to find the best setup for the generator based on (power generation) / (generator weight) rate. The winding will be made on the stator (typical design) and later on the translator to reach the best coil design.

	Tooth width=25mm stator winded	Tooth width=25mm translator winded
R=200mm	Setup: 1	Setup: 3
R=400mm	Setup: 2	Setup: 4

Setup on 25mm tooth width:

- ❖ The objective is to calculate a 1,5m translator over a 3m stator meeting the specs: 6000W on a 3m travel at 12000N (only up generation cycle)
- ❖ An electrical density of 3 A/mm² will be considered as a starting point to ensure an optimal losses and thermic performance.
- ❖ Translator teeth height will be two times the tooth width to improve the reluctance ratio of aligned to unaligned position.
- ❖ Stator teeth height will be four times the tooth width to maximize the space for the coil without compromising the mechanical properties of the teeth. If a change on magnetic force is needed it can be increased or decreased later.
- ❖ Starting induction density of 1,6T is used ($\mu_r=604$.) later it can be fine adjusted to increase or decrease slightly the force done on translator.

$$Rm_{total} = Rm_{stator\ tooth} * 2 + Rm_{stator\ yoke} + Rm_{air\ gap} * 2 + Rm_{translator\ tooth} * 2 + Rm_{translator\ yoke}$$

$$Rm_{stator\ tooth} = \frac{1}{\mu} * \frac{l}{s} = \frac{1}{604 * (4\pi * 10^{-7})} * \frac{0,10}{0,025 * depth} = 5270,03 \left(\frac{1}{H}\right)/m$$

$$Rm_{stator\ yoke} = \frac{1}{\mu} * \frac{l}{s} = \frac{1}{604 * (4\pi * 10^{-7})} * \frac{0,15}{0,025 * depth} = 7905,05 \left(\frac{1}{H}\right)/m$$

$$Rm_{translator\ tooth} = \frac{1}{\mu} * \frac{l}{s} = \frac{1}{604 * (4\pi * 10^{-7})} * \frac{0,05}{0,025 * depth} = 2635,02 \left(\frac{1}{H}\right)/m$$

$$Rm_{translator\ yoke} = \frac{1}{\mu} * \frac{l}{s} = \frac{1}{604 * (4\pi * 10^{-7})} * \frac{0,15}{0,025 * depth} = 7905,05 \left(\frac{1}{H}\right)/m$$

$$Rm_{air\ gap} = \frac{1}{\mu} * \frac{l}{s} = \frac{1}{4\pi * 10^{-7}} * \frac{0,001}{0,025 * depth} = 31830,99 \left(\frac{1}{H}\right)/m$$

$$Rm_{total} = 5270,03 * 2 + 7905,05 + 31830,99 * 2 + 2635,02 * 2 + 7905,05 \\ = 95282,18 \left(\frac{1}{H}\right)/m$$

Then to reach the 1,6T the magnetic force must be:

$$\phi = B * Section = 1,6 * 0,025 * depth = 0,04 (Wb) * m$$

$$Fm = \phi * Rm = 0,04 * 95282,18 = 3811,29 A$$

$$Fm_{each\ coil} = \frac{3811,29}{2} = 1905,65 A$$

As the coil will be wined with 1mm diameter wires, the cross section of each wire is $0,7854\text{mm}^2$ and then each wire can carry:

$$\text{Current by wire} = \text{Electrical}_{density} * \text{Wire}_{section} = 3 * 0,7854 = 2,3562 \text{ A}$$

So to reach the magnetic force on the coil, the following turns of wire are needed:

$$\text{Wire}_{turns} = \frac{1905,65}{2,3562} = 809 \text{ turns}$$

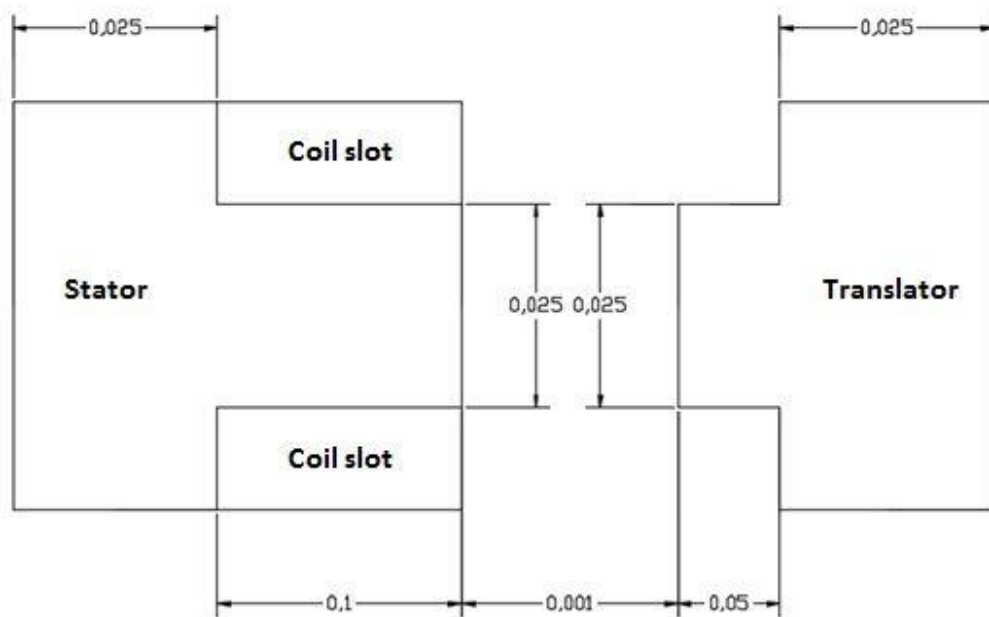
The filling factor due the round shape and the enamel is 0,6 so the final cross section of each coil slot must be:

$$\begin{aligned} \text{Needed slot}_{cross\ section} &= \frac{\text{wire}_{turns} * \text{wire}_{section}}{\text{filling}_{factor}} \\ \text{Needed slot}_{cross\ section} &= \frac{809 * 0,7854}{0,6} = 1058,98 \text{ mm}^2 \end{aligned}$$

With a rate on the stator tooth of 1:4 width over height it has an slot of:

$$\begin{aligned} \text{Slot}_{cross\ section} &= \frac{\text{tooth width}}{2} * (\text{tooth width} * 4) = \frac{0,025}{2} * (0,025 * 4) \\ &= 0,00125 \text{ m}^2 = 1250 \text{ mm}^2 \end{aligned}$$

So the starting tooth height is correct and it produces a slot for the coil with the desirable cross section. The remaining free space could be used for the dielectric separator on the slot profile.



Drawing 12: Teeth design based on 25mm setup with the stator wined

The yoke must be adjusted to decrease the generator volume, at starting point it will be adjusted for two intermediate positions:

- Stator yoke adjust to 200mm radius:

$$Stator\ yoke_{radius\ ratio} = \frac{Stator\ yoke_{radius}}{Air\ gap\ radius}$$

$$Stator\ yoke_{radius\ ratio} = \frac{Air\ gap_{radius} + Stator\ tooth_{height} + Stator\ yoke_{height}}{0,2}$$

$$Stator\ yoke_{radius\ ratio} = \frac{0,2 + 0,025 * 4 + 0,025}{0,2} = 1,625$$

So the stator yoke is 62,5% bigger than necessary, so it will be decreased to:

$$Stator\ yoke_{height} = \frac{Starting\ height}{ratio} = \frac{0,025}{1,625} = 0,01538\ m$$

- Translator yoke adjust to 200mm radius:

$$Translator\ yoke_{radius\ ratio} = \frac{Translator\ yoke_{radius}}{Air\ gap\ radius}$$

$$Trans.\ yoke_{radius\ ratio} = \frac{Air\ gap_{radius} - (Trans.\ tooth_{height} + Trans.\ yoke_{height})}{0,2}$$

$$Translator\ yoke_{radius\ ratio} = \frac{0,2 - (0,025 * 2 + 0,025)}{0,2} = 0,6250$$

So the translator yoke is 37,5% smaller than necessary, so it will be increased to:

$$Translator\ yoke_{height} = \frac{Starting\ height}{ratio} = \frac{0,025}{0,625} = 0,04\ m$$

- Stator yoke adjust to 400mm radius:

$$Stator\ yoke_{radius\ ratio} = \frac{Stator\ yoke_{radius}}{Air\ gap\ radius}$$

$$Stator\ yoke_{radius\ ratio} = \frac{Air\ gap_{radius} + Stator\ tooth_{height} + Stator\ yoke_{height}}{0,2}$$

$$Stator\ yoke_{radius\ ratio} = \frac{0,4 + 0,025 * 4 + 0,025}{0,4} = 1,3125$$

So the stator yoke is 31,25% bigger than necessary, so it will be decreased to:

$$Stator\ yoke_{height} = \frac{Starting\ height}{ratio} = \frac{0,025}{1,3125} = 0,01905\ m$$

- Translator yoke adjust to 400mm radius:

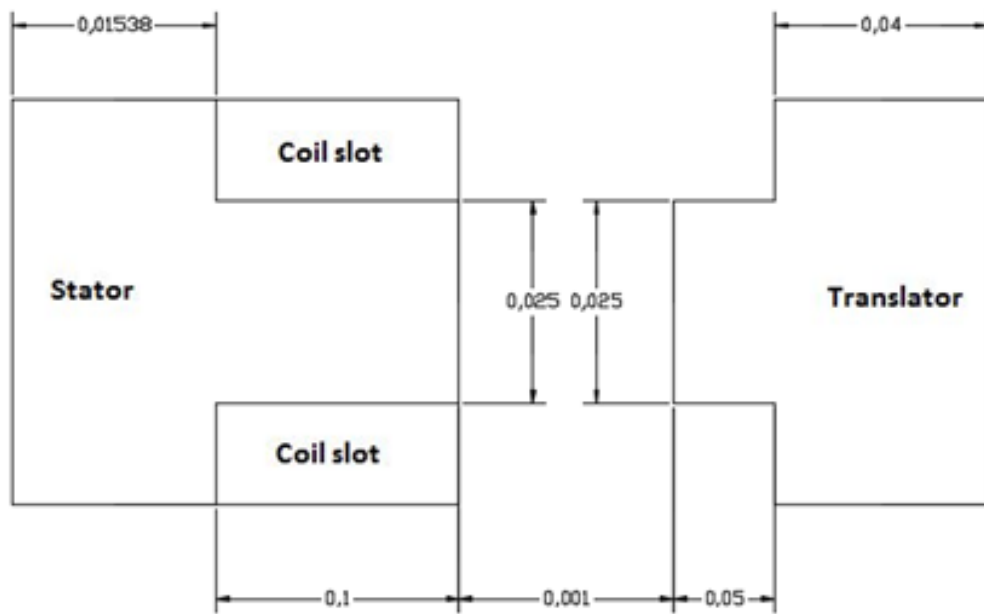
$$Translator\ yoke_{radius\ ratio} = \frac{Translator\ yoke_{radius}}{Air\ gap\ radius}$$

$$Trans.\ yoke_{radius\ ratio} = \frac{Air\ gap_{radius} - (Trans.\ tooth_{height} + Trans.\ yoke_{height})}{0,2}$$

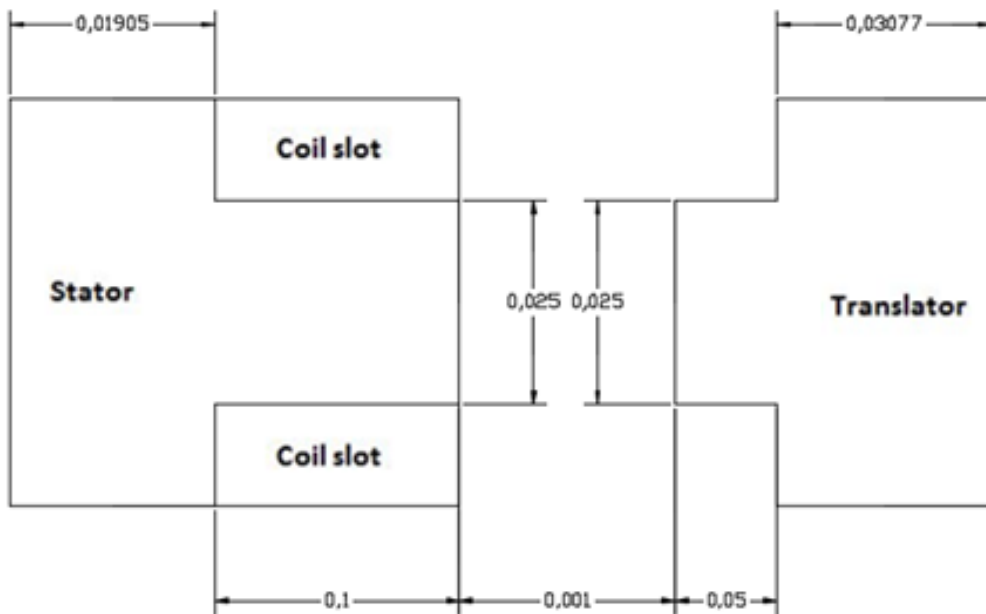
$$Translator\ yoke_{radius\ ratio} = \frac{0,4 - (0,025 * 2 + 0,025)}{0,4} = 0,8125$$

So the translator yoke is 18,75% smaller than necessary, so it will be increased to:

$$Translator\ yoke_{height} = \frac{Starting\ height}{ratio} = \frac{0,025}{0,8125} = 0,03077\ m$$

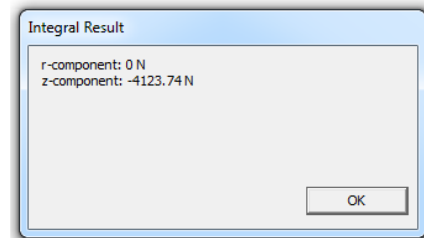
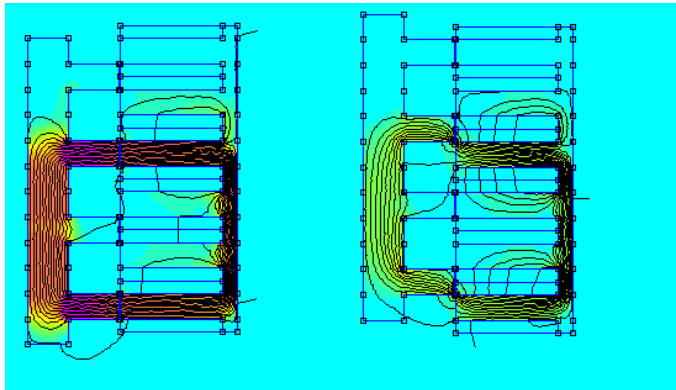


Drawing 13: Teeth design based on 25mm setup (yoke corrected at 200mm radius)

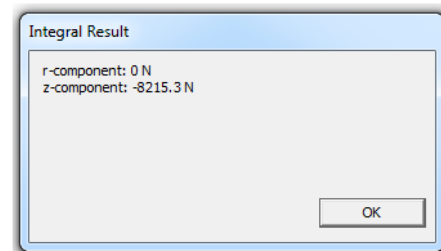
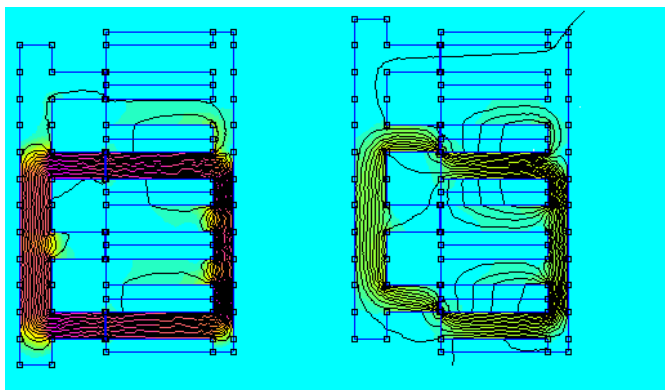


Drawing 14: Teeth design based on 25mm setup (yoke corrected at 400mm radius)

Now the **25mm tooth setup will be simulated** at the two radius positions to check the best option (meaning more radius, more power but more volume). It will be simulated over electromagnetic finite elements software and the outputs showed here:



Drawing 15: 200mm radius simulation, obtaining 4123N over 4995kg of generator mass



Drawing 16: 400mm radius simulation, obtaining 8215N over 9315kg of generator mass

As we can see on the previous simulations the generator force over the mass follows a linear rise over the radius position. The required specs are 12000N (at 1,5m of linear generator) for that in the testing section of 0,3m we need a minimum force of: 2400N.

For that in this tooth setup the best radius position for the generator is with the air gap at 200mm radius for a lowest weight with the enough required force.

On the next setup the coils will be moved to the translator in order to reduce the copper and the weight due to the stator length doubles the translator length.

Setup on 40mm tooth width:

- ❖ The objective is to calculate a 1,5m translator over a 3m stator meeting the specs: 6000W on a 6m travel at 6000N (up and down generation cycle)
- ❖ An electrical density of 3 A/mm² will be considered as starting point to ensure an optimal losses and thermic performance.
- ❖ Translator teeth height will have the same dimensions as the width. If a change on magnetic force is needed it can be increased or decreased later.
- ❖ Stator teeth height will be half of the width pursuing the lowest generator weight but trying to reach a 1:5 reluctance ratio over aligned to unaligned.
- ❖ Starting induction density of 1,6T is used ($\mu_r=604$.) later it can be fine adjusted to increase or decrease slightly the force done on translator.

$$Rm_{total} = Rm_{stator\ tooth} * 2 + Rm_{stator\ yoke} + Rm_{air\ gap} * 2 + Rm_{translator\ tooth} * 2 + Rm_{translator\ yoke}$$

$$Rm_{stator\ tooth} = \frac{1}{\mu} * \frac{l}{s} = \frac{1}{604 * (4\pi * 10^{-7})} * \frac{0,02}{0,04 * depth} = 658,75 \left(\frac{1}{H}\right)/m$$

$$Rm_{stator\ yoke} = \frac{1}{\mu} * \frac{l}{s} = \frac{1}{604 * (4\pi * 10^{-7})} * \frac{0,24}{0,04 * depth} = 7905,05 \left(\frac{1}{H}\right)/m$$

$$Rm_{translator\ tooth} = \frac{1}{\mu} * \frac{l}{s} = \frac{1}{604 * (4\pi * 10^{-7})} * \frac{0,04}{0,04 * depth} = 1317,51 \left(\frac{1}{H}\right)/m$$

$$Rm_{translator\ yoke} = \frac{1}{\mu} * \frac{l}{s} = \frac{1}{604 * (4\pi * 10^{-7})} * \frac{0,24}{0,04 * depth} = 7905,05 \left(\frac{1}{H}\right)/m$$

$$Rm_{air\ gap} = \frac{1}{\mu} * \frac{l}{s} = \frac{1}{4\pi * 10^{-7}} * \frac{0,001}{0,04 * depth} = 19894,37 \left(\frac{1}{H}\right)/m$$

$$Rm_{total} = 658,75 * 2 + 7905,05 + 19894,37 * 2 + 1317,51 * 2 + 7905,05 \\ = 59551,36 \left(\frac{1}{H}\right)/m$$

Then to reach the 1,6T the magnetic force must be:

$$\phi = B * Section = 1,6 * 0,04 * depth = 0,064 (Wb) * m$$

$$Fm = \phi * Rm = 0,064 * 59551,36 = 3811,29 A$$

$$Fm_{each\ coil} = \frac{3811,29}{2} = 1905,65 A$$

As the coil will be wined with 1mm diameter wires, the cross section of each wire is $0,7854\text{mm}^2$ and then each wire can carry:

$$\text{Current by wire} = \text{Electrical}_{density} * \text{Wire}_{section} = 3 * 0,7854 = 2,3562 \text{ A}$$

So to reach the magnetic force on the coil, the following turns of wire are needed:

$$\text{Wire}_{turns} = \frac{1905,65}{2,3562} = 809 \text{ turns}$$

The filling factor due the round shape and the enamel is 0,6 so the final cross section of each coil slot must be:

$$\begin{aligned} \text{Needed slot}_{cross\ section} &= \frac{\text{wire}_{turns} * \text{wire}_{section}}{\text{filling}_{factor}} \\ \text{Needed slot}_{cross\ section} &= \frac{809 * 0,7854}{0,6} = 1058,98 \text{ mm}^2 \end{aligned}$$

With a rate on the translator tooth of 1:1 width over height it has a slot of:

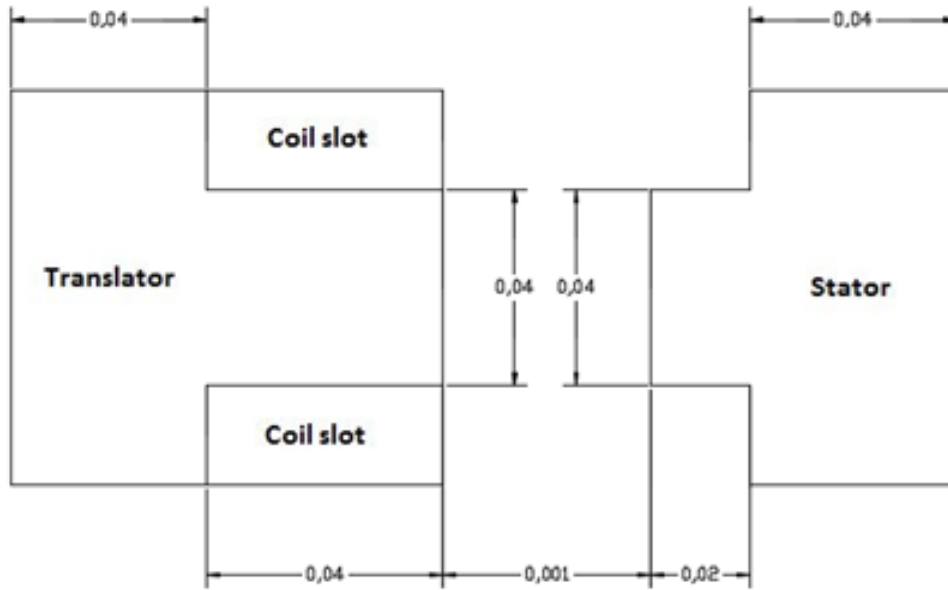
$$\begin{aligned} \text{Slot}_{cross\ section} &= \frac{\text{tooth width}}{2} * \text{tooth height} = \frac{0,04}{2} * 0,04 = 0,0008 \text{ m}^2 \\ &= 800 \text{ mm}^2 \end{aligned}$$

In that case to fit the conductors needed on the slot square wires will be used with a filling factor of 0,8 to reach a needed slot of: $\frac{809*0,7854}{0,8} = 794,24 \text{ mm}^2$ and wires of 1mm^2 will be used fitting in every slot 795 wires with 3A current on each.

$$\text{Current by wire} = \text{Electrical}_{density} * \text{Wire}_{section} = 3 * 1 = 3 \text{ A}$$

$$\text{Wire}_{turns} = \frac{1905,65}{3} = 636 \text{ turns}$$

$$\text{Needed slot}_{cross\ section} = \frac{636 * 1}{0,8} = 795 \text{ mm}^2$$



Drawing 17: Teeth design based on 40mm setup with the translator winded

The yoke must be adjusted to decrease the generator volume, at starting point it will be adjusted for two intermediate positions:

- Stator yoke adjust to 200mm radius:

$$Stator\ yoke_{radius\ ratio} = \frac{Stator\ yoke_{radius}}{Air\ gap\ radius}$$

$$Stator\ yoke_{radius\ ratio} = \frac{Air\ gap_{radius} + Stator\ tooth_{height} + Stator\ yoke_{height}}{0,2}$$

$$Stator\ yoke_{radius\ ratio} = \frac{0,2 + 0,02 + 0,04}{0,2} = 1,30$$

So the stator yoke is 30% bigger than necessary, so it will be decreased to:

$$Stator\ yoke_{height} = \frac{Starting\ height}{ratio} = \frac{0,04}{1,30} = 0,03077\ m$$

- Translator yoke adjust to 200mm radius:

$$Translator\ yoke_{radius\ ratio} = \frac{Translator\ yoke_{radius}}{Air\ gap\ radius}$$

$$Trans.yoke_{radius\ ratio} = \frac{Air\ gap_{radius} - (Trans.tooth_{height} + Trans.yoke_{height})}{0,2}$$

$$Translator\ yoke_{radius\ ratio} = \frac{0,2 - (0,04 + 0,04)}{0,2} = 0,60$$

So the translator yoke is 40% smaller than necessary, so it will be increased to:

$$Translator\ yoke_{height} = \frac{Starting\ height}{ratio} = \frac{0,04}{0,60} = 0,06667\ m$$

- Stator yoke adjust to 400mm radius:

$$Stator\ yoke_{radius\ ratio} = \frac{Stator\ yoke_{radius}}{Air\ gap\ radius}$$

$$Stator\ yoke_{radius\ ratio} = \frac{Air\ gap_{radius} + Stator\ tooth_{height} + Stator\ yoke_{height}}{0,4}$$

$$Stator\ yoke_{radius\ ratio} = \frac{0,4 + 0,02 + 0,04}{0,4} = 1,15$$

So the stator yoke is 15% bigger than necessary, so it will be decreased to:

$$Stator\ yoke_{height} = \frac{Starting\ height}{ratio} = \frac{0,04}{1,15} = 0,03478\ m$$

- Translator yoke adjust to 400mm radius:

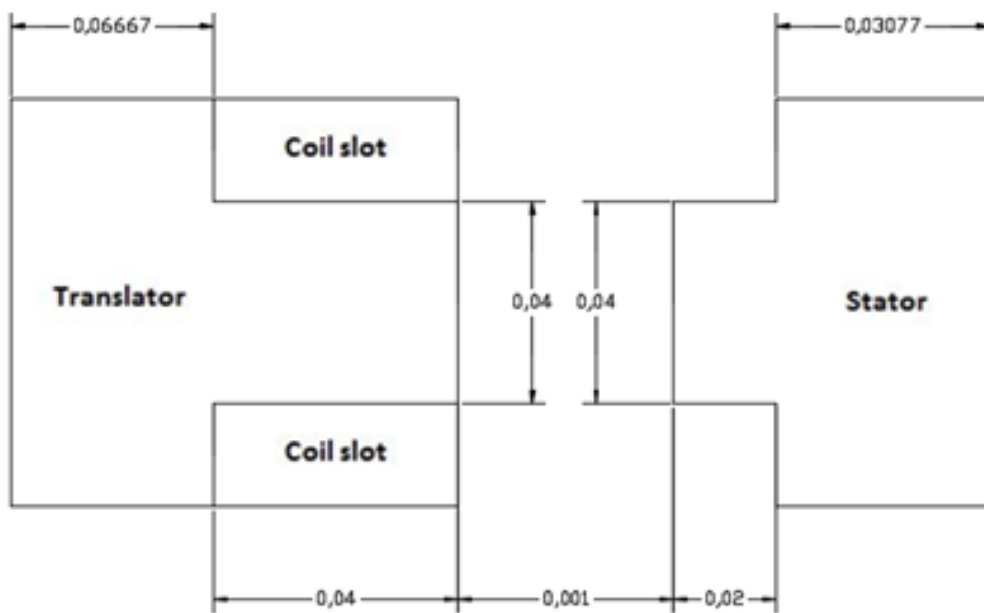
$$Translator\ yoke_{radius\ ratio} = \frac{Translator\ yoke_{radius}}{Air\ gap\ radius}$$

$$Trans.yoke_{radius\ ratio} = \frac{Air\ gap_{radius} - (Trans.tooth_{height} + Trans.yoke_{height})}{0,4}$$

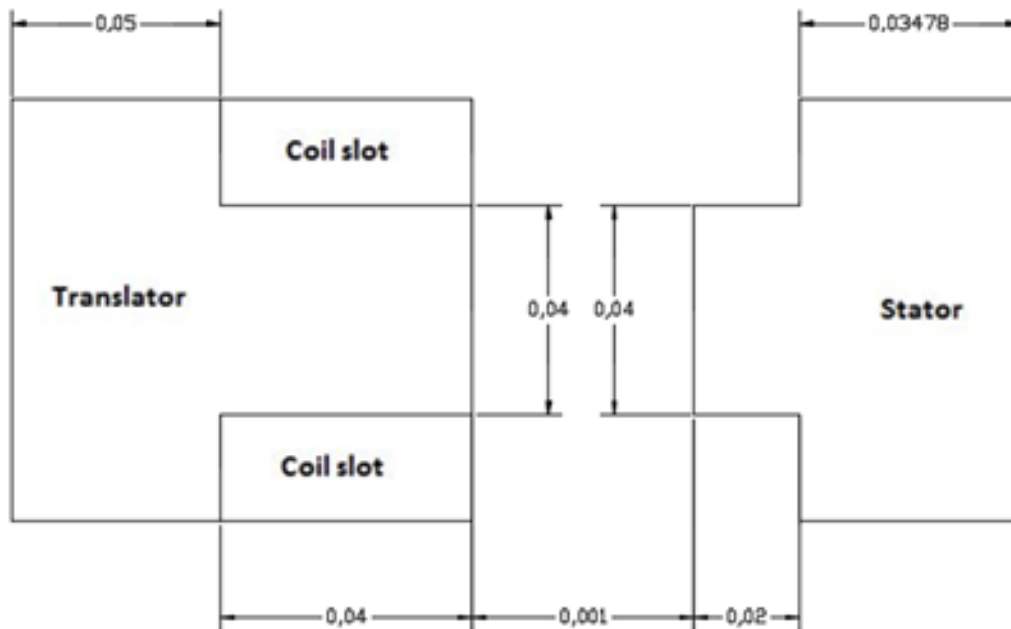
$$Translator\ yoke_{radius\ ratio} = \frac{0,4 - (0,04 + 0,04)}{0,4} = 0,80$$

So the translator yoke is 20% smaller than necessary, so it will be increased to:

$$Translator\ yoke_{height} = \frac{Starting\ height}{ratio} = \frac{0,04}{0,80} = 0,05\ m$$

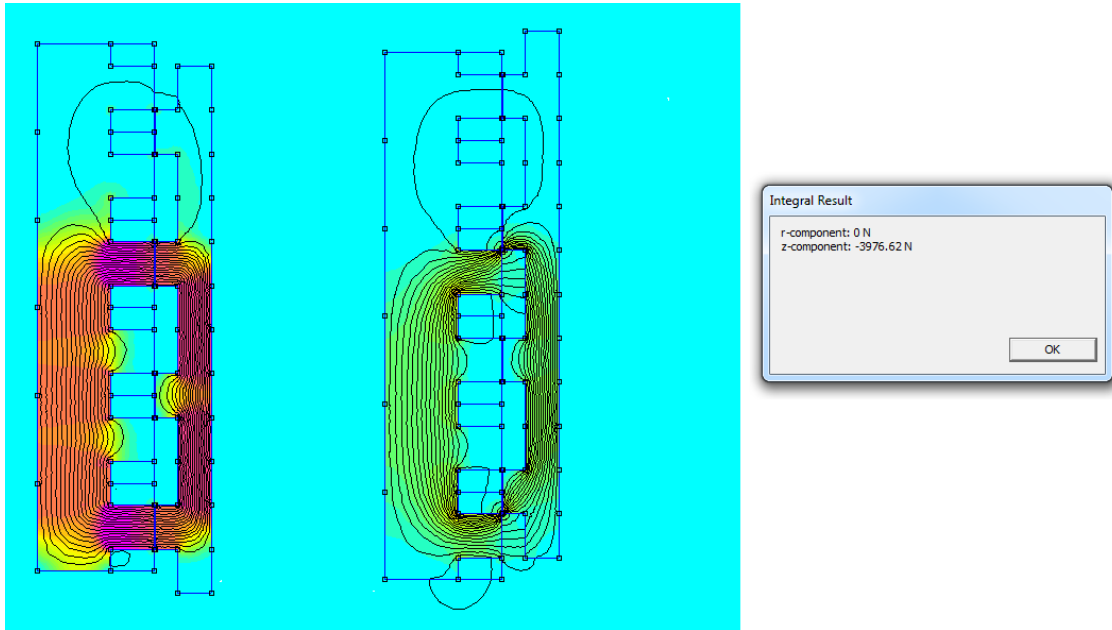


Drawing 18: Teeth design based on 40mm setup (yoke corrected at 200mm radius)

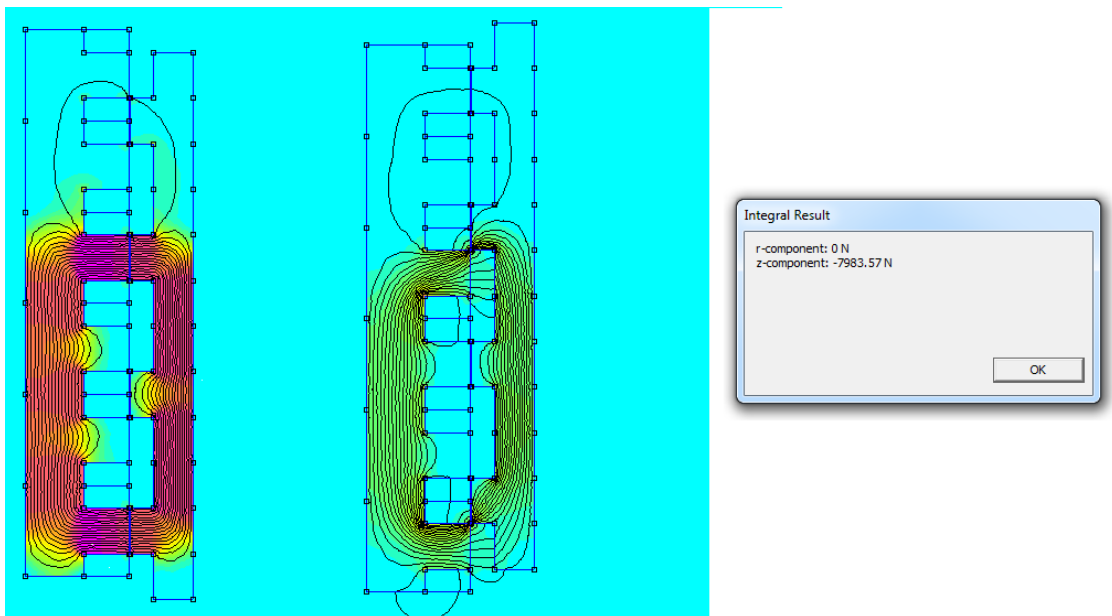


Drawing 19: Teeth design based on 40mm setup (yoke corrected at 400mm radius)

Now the **40mm tooth setup will be simulated** at the two radius positions to check the best option (meaning more radius, more power but more volume). It will be simulated over electromagnetic finite elements software and the outputs showed here:

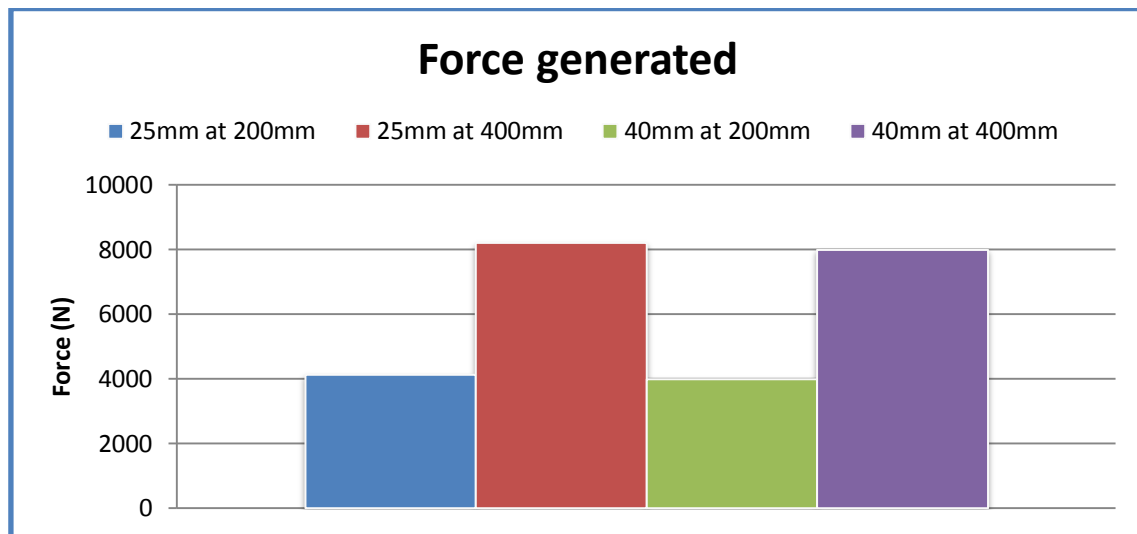


Drawing 20: 40mm at 200mm radius simulation, obtaining 4000N over 2350kg of generator mass

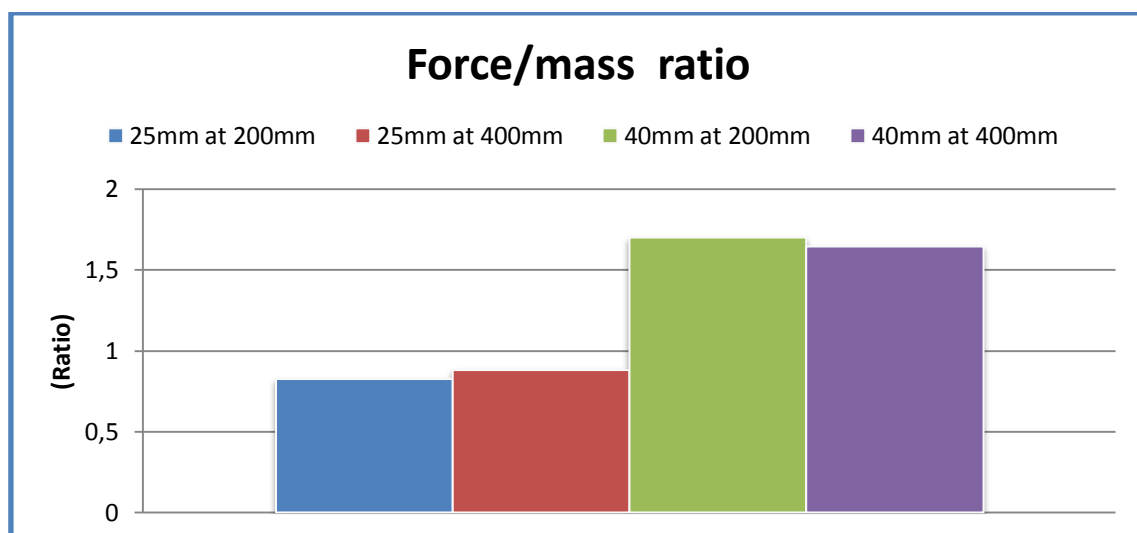


Drawing 21: 40mm at 400mm radius simulation, obtaining 8000N over 4860kg of generator mass

The next graphs show the force and the calculated ratio between the force generated and the generator mass:



Statistic 12: Generator force developed

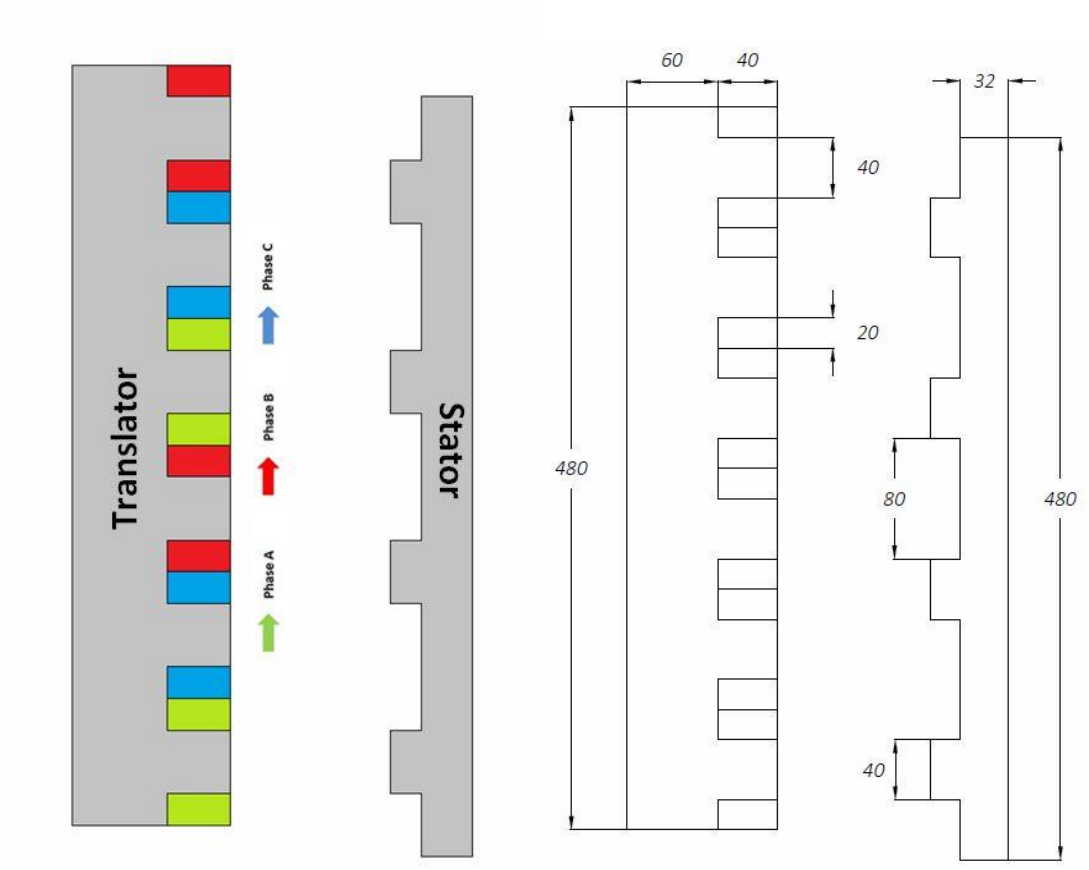


Statistic 13: Generator force and mass ratios

As clearly exposed above the best tooth setup is the one based on 40mm tooth width and the translator winded as been expected, because the translator lengths the half of the stator and thanks to it the copper is halved saving price and weight. Additionally the magnetic circuit design with shorter but wider tooth improves the flux helping to increase the force done (later translated to mechanical energy entry).

When only 6000N force are needed, the best radius position of the air gap is at 200mm and with an average force of 4000N developed by every 50cm of generator is possible to use only 1m of translator instead of 1,5m reducing even more the final generator weight.

Generator teeth design and winding:

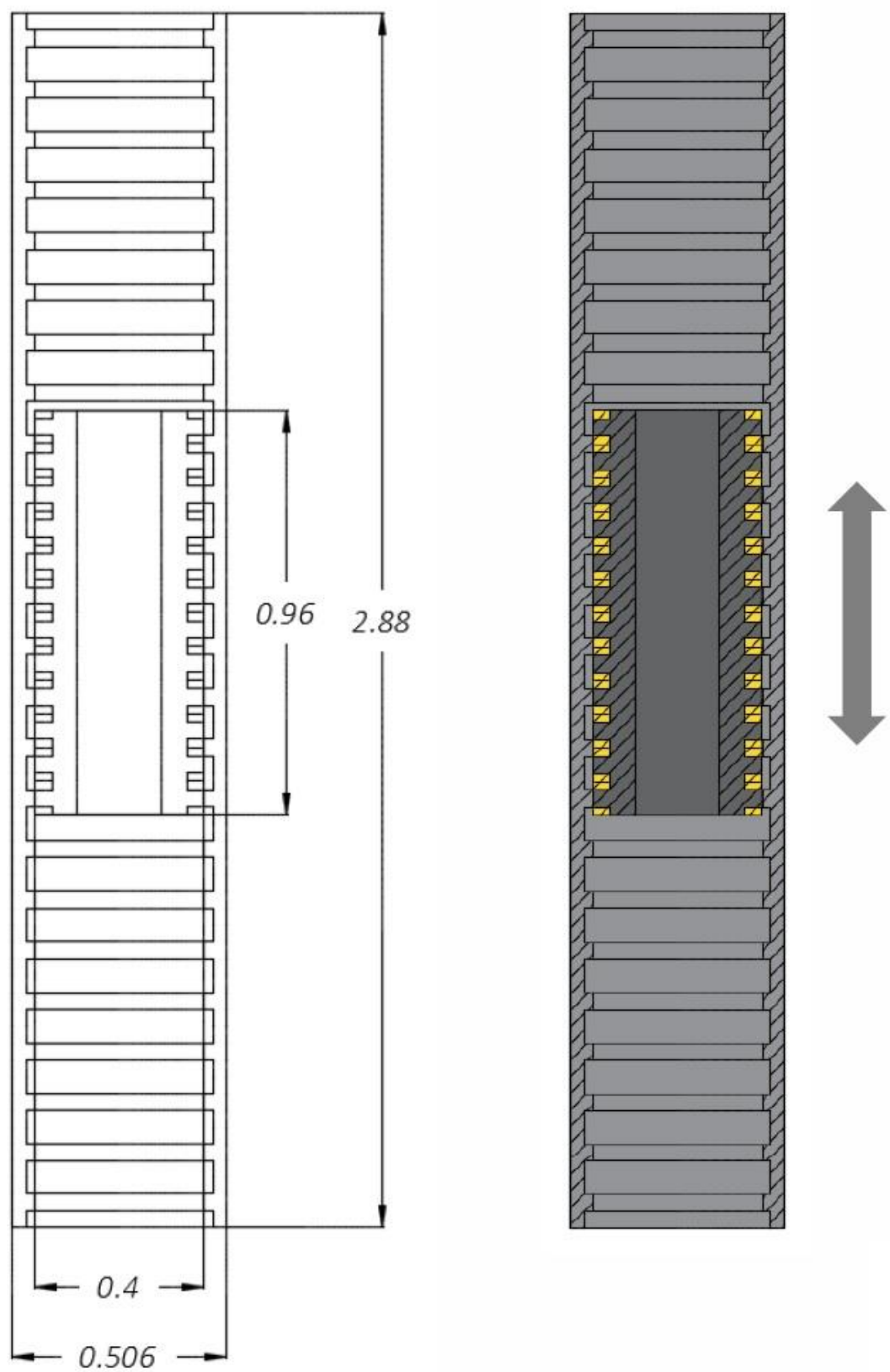


Drawing 22: Generator teeth design showing one stator and translator section (air gap = 1mm)

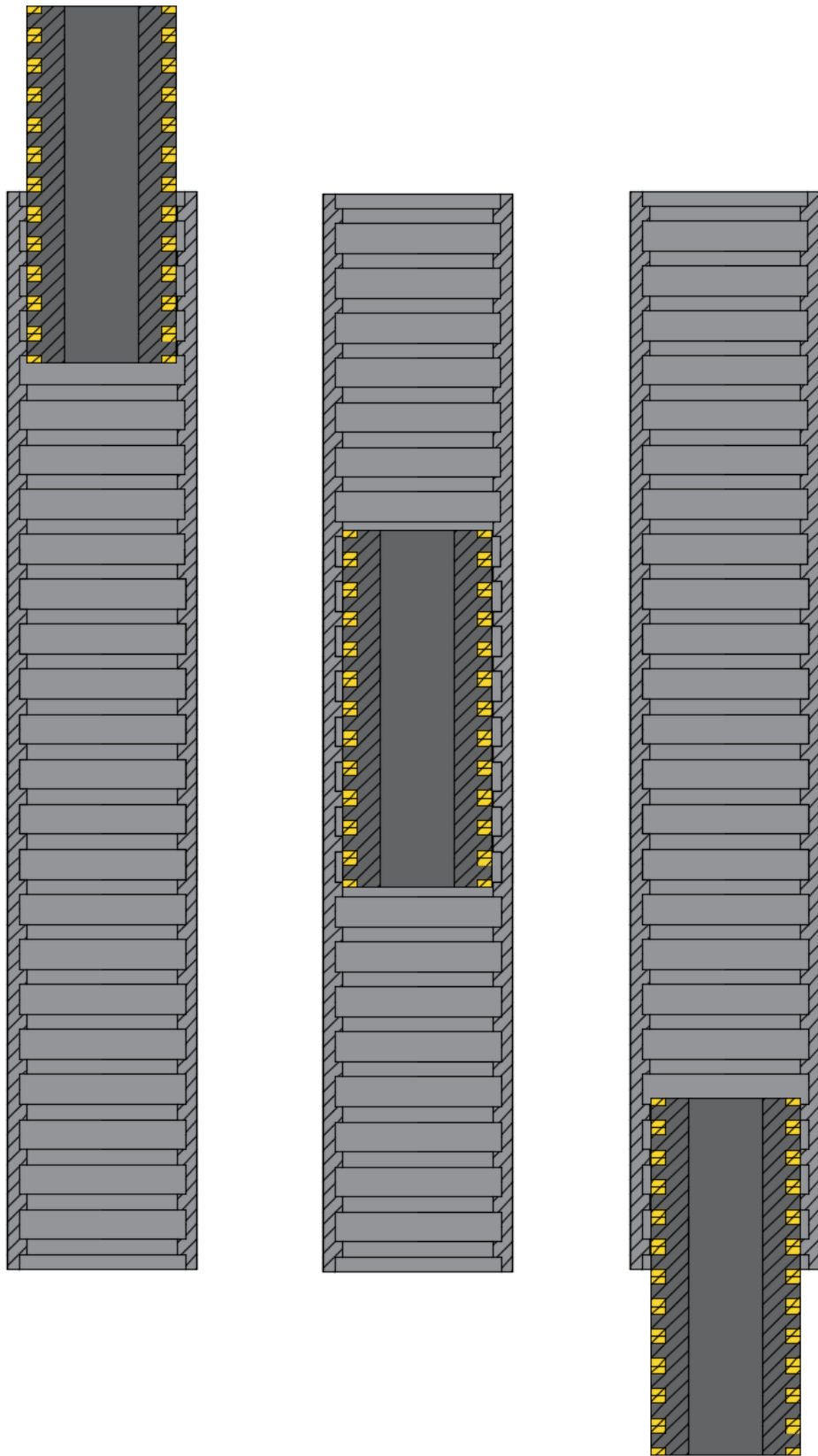
Generator setup:

- **Translator length** = 960mm (two sections of 48mm each)
- **Stator length**: 2880mm (six sections of 48mm each)
- **Air gap**: 1mm (based on manufacturing technology)
- **Translator teeth width**: 40mm
- **Translator teeth height**: 40mm
- **Translator yoke height**: 60mm (fine adjusted in simulation)
- **Translator coil slots**: $20 \times 40\text{mm} = 800\text{mm}^2$
- **Stator teeth width**: 40mm
- **Stator teeth height**: 20mm
- **Stator yoke height**: 32mm (fine adjusted in simulation)
- **Generator mass**: 1975 kg (695kg related to the translator)

Generator 2D cut drawing:



Drawing 23: Generator 2D cut drawing and motion display (m)



Drawing 24: Generator down to up wave motion and translator displacement

Now the average force and energy balances between mechanical and electrical energy will be calculated.

As the generator weight is so important and for that the generator is working on a high saturated material, the regular formulas based on linear systems cannot be used here:

$$F = \frac{1}{2} * I^2 * \frac{dL}{dx}$$

$$\text{Mechanical power} = F * v$$

$$E = \frac{d\psi}{dt}$$

$$\text{Electrical power (discounting non usable energy)} = \frac{E * I}{2}$$

Then the energy balance and powers must be calculated by energy and coenergy curves obtained simulating the generator from 0 to rated current at two different positions, aligned and unaligned tooth.

Coenergy will show the total amount of energy that the system can store and share between the electrical and mechanical energies. And with it the average force and power output can be calculated.

$$W (\text{energy}) = \int_{\psi_1}^{\psi_2} I * d\psi$$

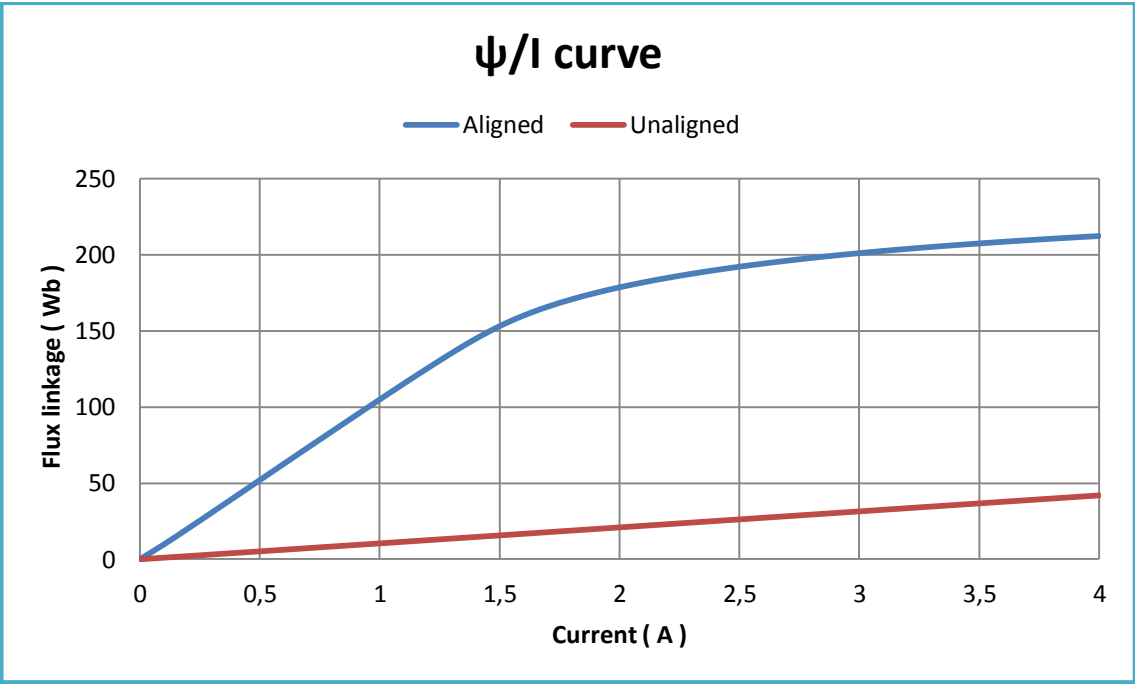
$$W' (\text{coenergy}) = \int_{I_1}^{I_2} \psi * dI$$

$$F = \frac{dW'}{dx}$$

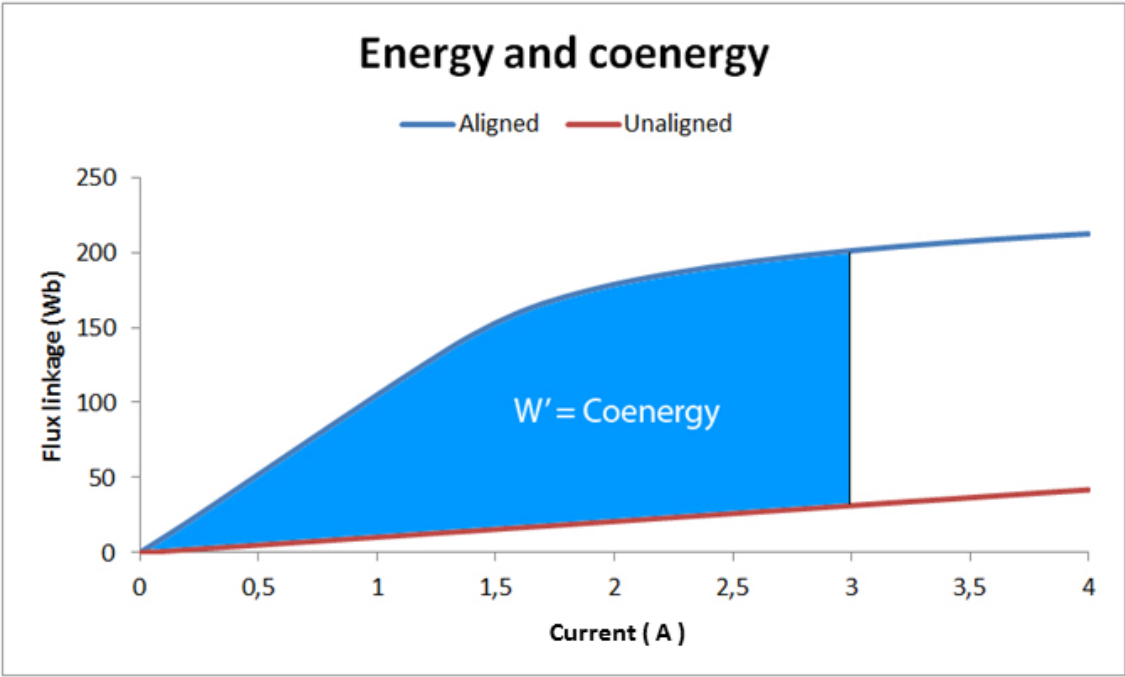
$$\text{Mechanical power} = \frac{dW'}{dx} * \frac{dx}{dt} = \frac{dW'}{dt}$$

$$\text{Electrical power} = \text{Mechanical power} = \frac{dW'}{dt}$$

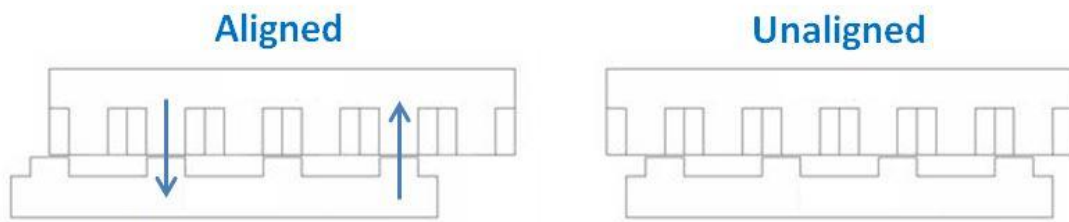
Using the finite elements software to obtain the aligned-unaligned data the curves can be drawn and the coenergy calculated:



Statistic 14: Flux linkage/current aligned and unaligned position



Statistic 15: Generator coenergy for aligned to unaligned position

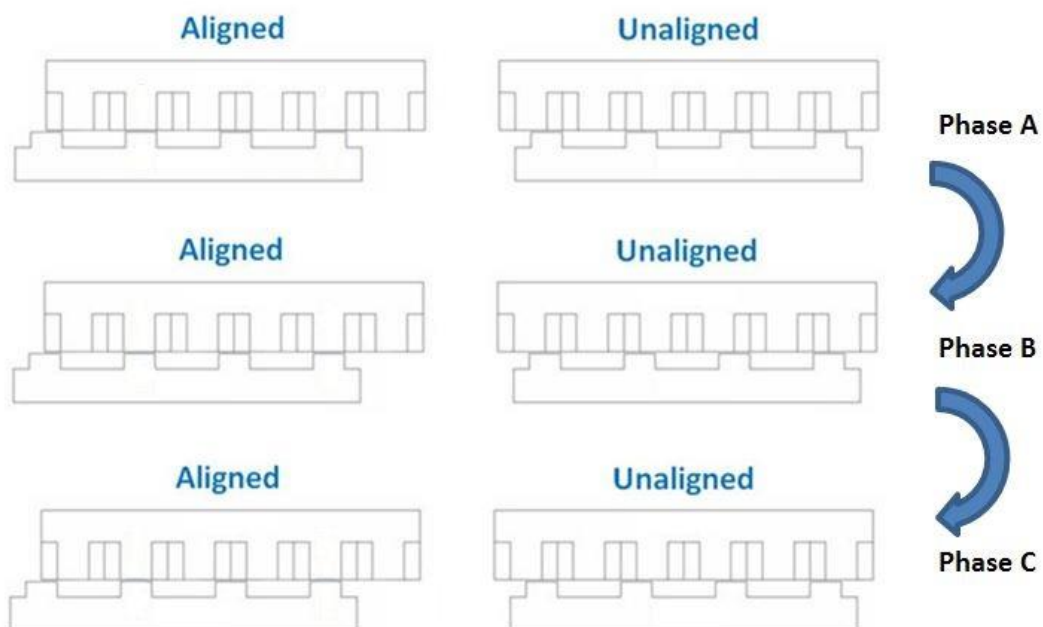


Picture 18: Aligned to unaligned positions

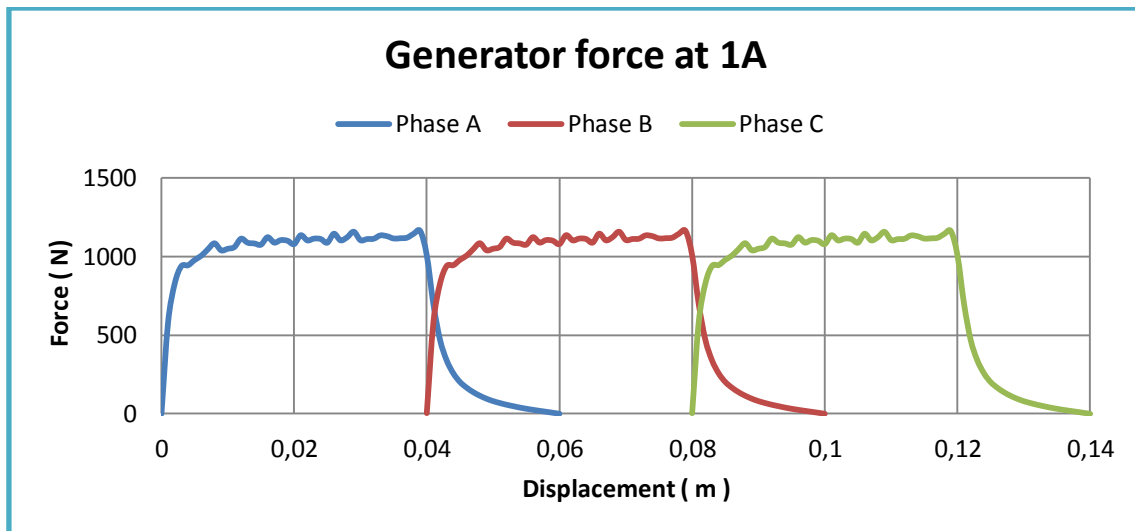
With the previous curves the **energy balance** can be calculated:

- $W' = \text{Coenergy} = 361,99 \text{ J}$ (integrating the curve)
- $F = \frac{dW'}{dx} = \frac{361,99}{0,06} = 6033 \text{ N}$
- $\text{Electrical power} = \text{Mechanical power} = \frac{dW'}{dt} = \frac{361,99}{0,06} = 6033 \text{ W}$

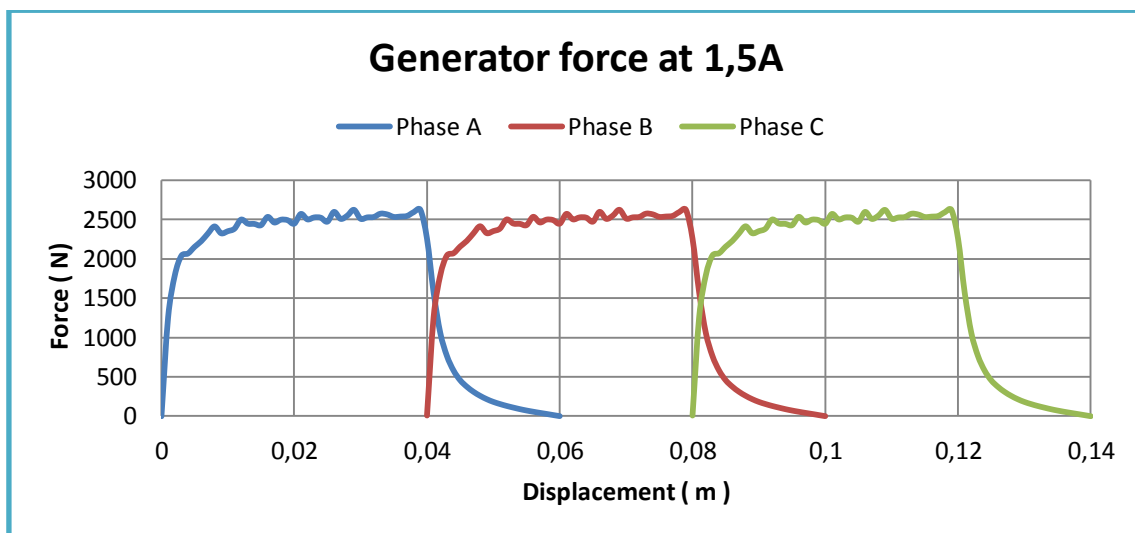
These values supports the design and the next deeper simulation will take an entire cycle to **obtain the force, flux and voltage generated in each phase on one sequence**:



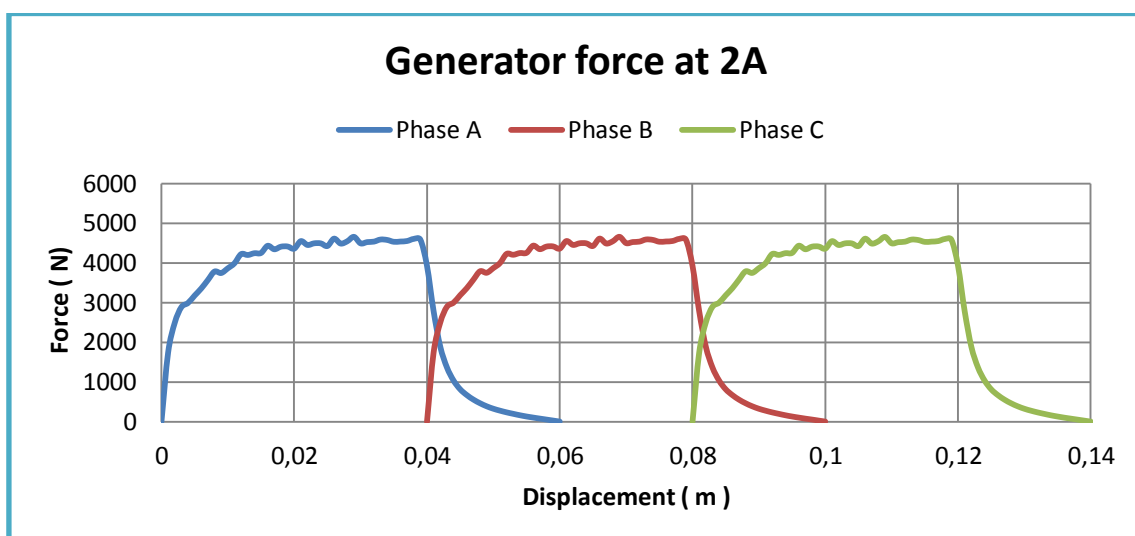
Picture 19: Simulation sequence of the three phases



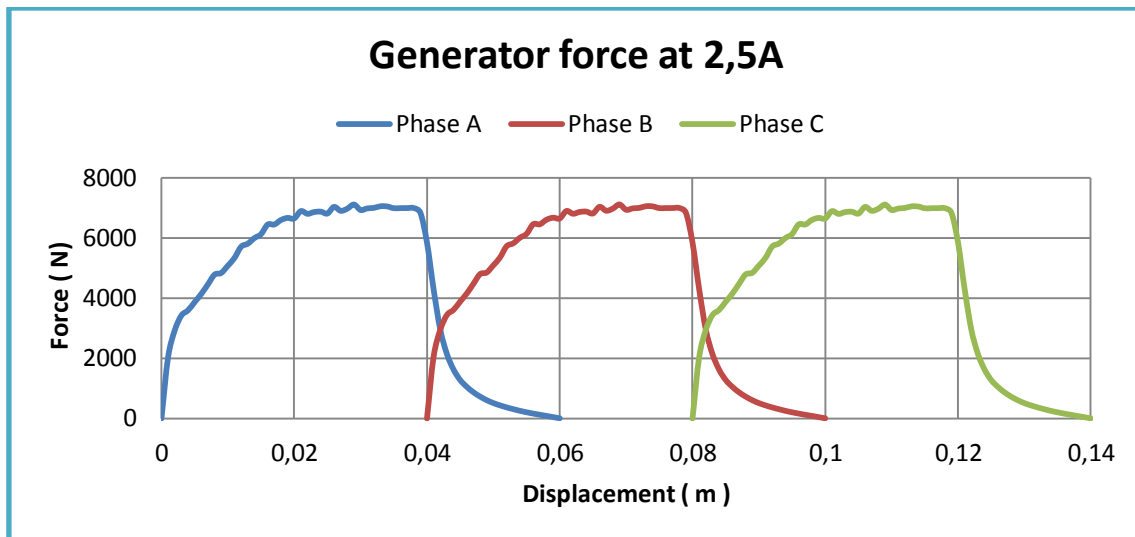
Statistic 16: Average phase force = 1082 N



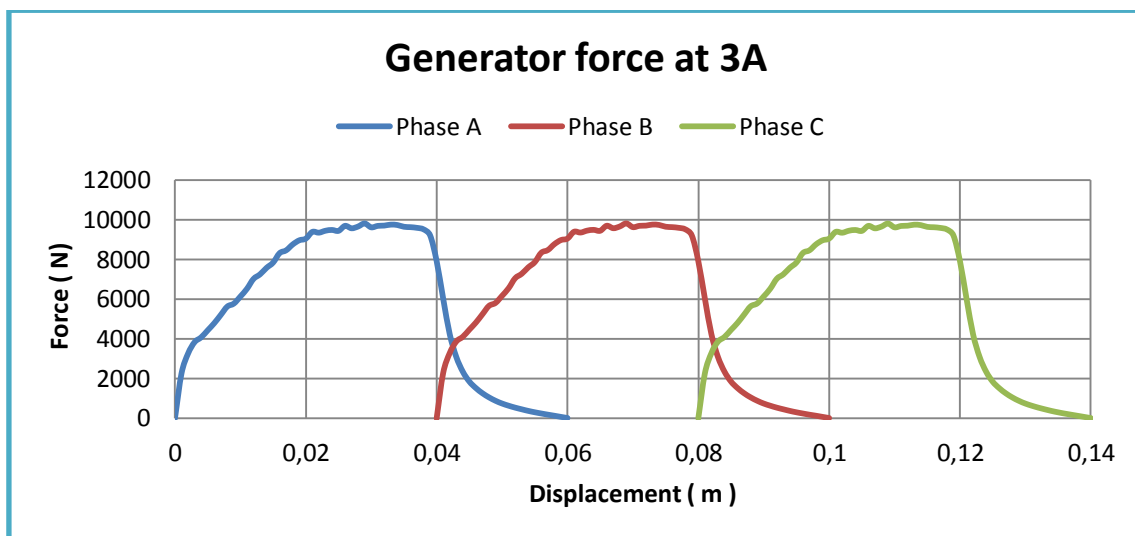
Statistic 17: Average phase force = 2441 N



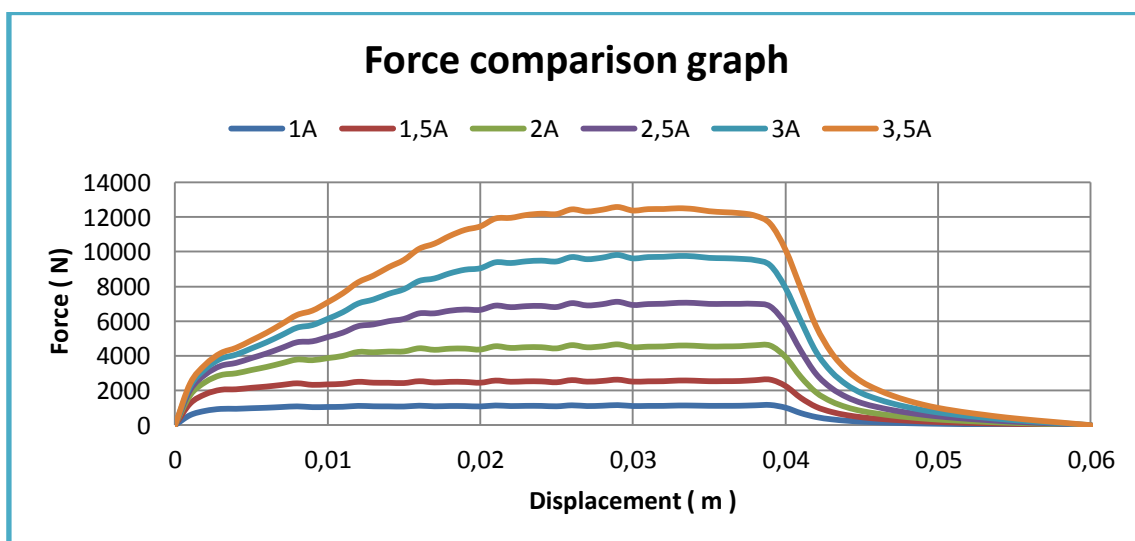
Statistic 18: Average phase force = 4190 N



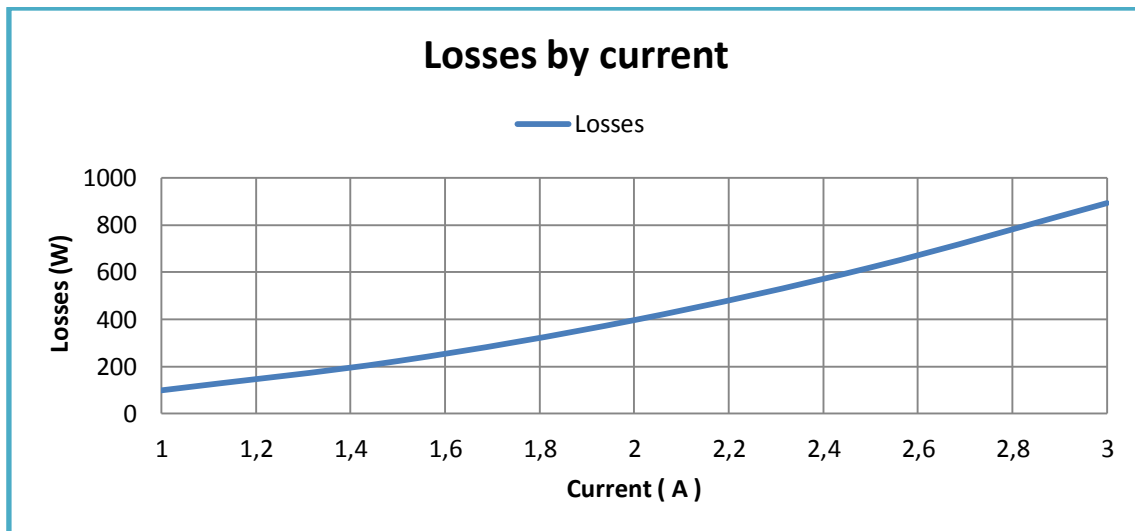
Statistic 19: Average phase force = 6101 N



Statistic 20: Average phase force = 8072 N



Statistic 21: Phase force comparison by current



Statistic 22: Losses comparison by current

In the previous graphs on different working conditions it is **possible to deduce that:**

- As the current increases the saturation too and the generator becomes smaller because it will generate more power with less translator length, but in the other way the force is warped and is more narrow and peaked making the generator motion more rough by the ripple. For that reason is important to find an optimal point between the generator mass and the generator smoothness.
- The optimal switching point between phases without overlapping is situated at the crossing phases point, from 0,002 to 0,042 of each phase so it will provide the more smoothness switching point with maximum generation:

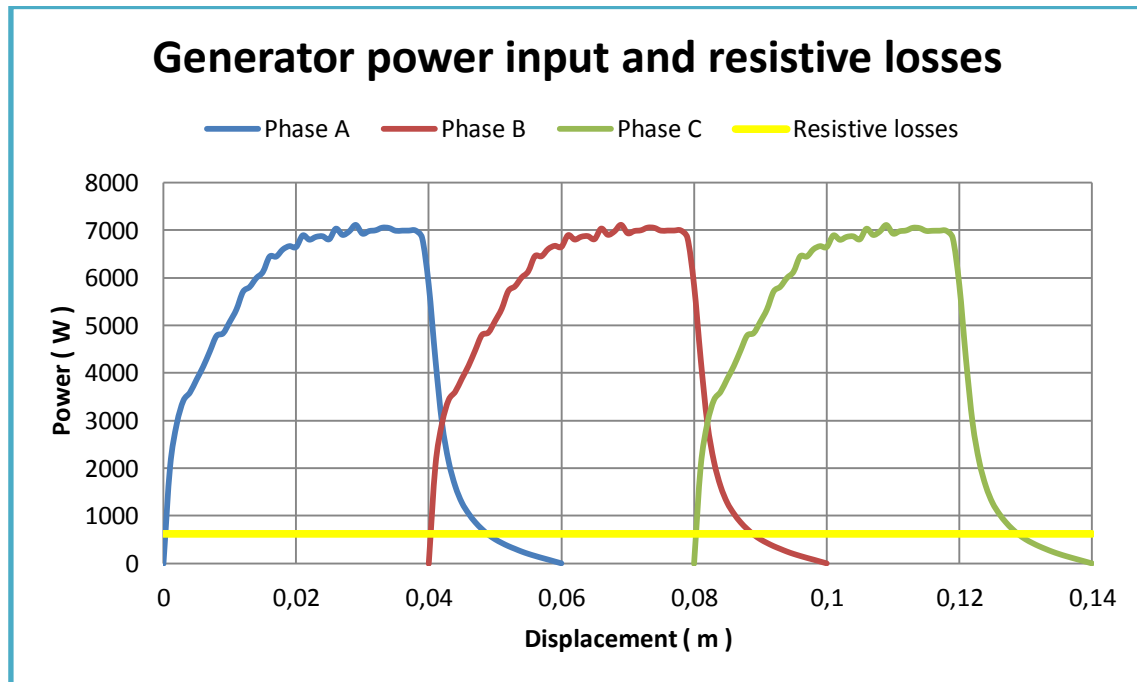
Switch position (Phase A): 0,002 (ON) → 0,042 (OFF)

Switch position (Phase B): 0,042(ON) → 0,082(OFF)

Switch position (Phase C): 0,082(ON) → 0,122(OFF)

- The ideal current to obtain the needed force (6000N) is situated at 2,5A providing an average force of 6100N.
- The force is higher than the calculated with coenergy because coenergy calculation is based on an entire phase cycle from 0 to 60mm and on the graphs the average force is calculated from the switching points 0,002 to 0,042. For that reason it is possible to decrease the current maintaining the average force.

Now the power generation graph will be compared with the resistive losses on the generator copper wires at 2,5A to obtain the generation output and the generator performance:



Statistic 23: Resistive losses = 620 W (power input = mechanical power)

The mechanical energy input minus the resistive losses give the generator electrical energy output and the **generator performance**:

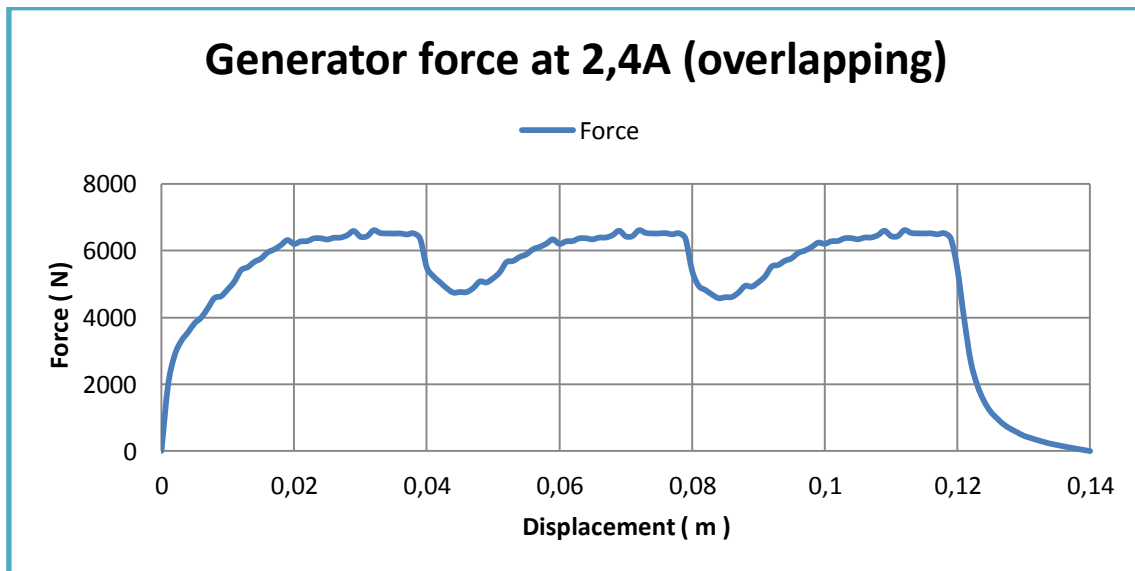
$$\eta = \frac{\text{Average power output}}{\text{Average power input}} = \frac{5466}{6102} = 0,8958 \rightarrow \mathbf{89,58 \%}$$

Once the generator design is validated and working properly, a **final adjustment** will be made to:

- Improve smoothness
- Adjust the working voltage

There are two ways to improve the generator smoothness. One of them consists on decreasing the current making the force waveform better but making the translator bigger, so this will increase so much the generator final weight to obtain a proper force waveform being the weight an extremely critical point in the project, for that reason the second option will be made consisting on an overlapping between phases avoiding the low force peaks and getting a more regular force over the generator motion. But with a phase overlap, losses will be increased because half of the time will be two active phases, for that reason the losses will be increased up to 50% more but at the same time more mechanical energy could be transferred to electrical energy thanks to exploiting the phase travel until the end.

To avoid raising the average power input that was already right, a small decrease on current must be applied on the generator in order to maintain the same 6000W of input power.



Statistic 24: Average force = 5924,41 N

Extended phase sequence:

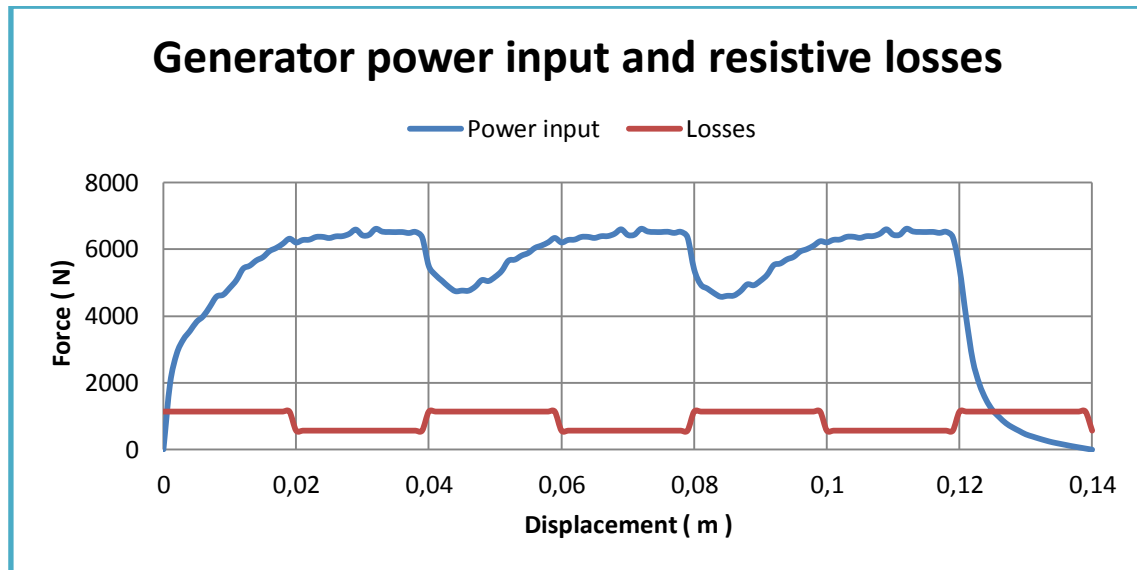
Switch position (Phase A): 0,000 (ON) → 0,060 (OFF)

Switch position (Phase B): 0,040(ON) → 0,100(OFF)

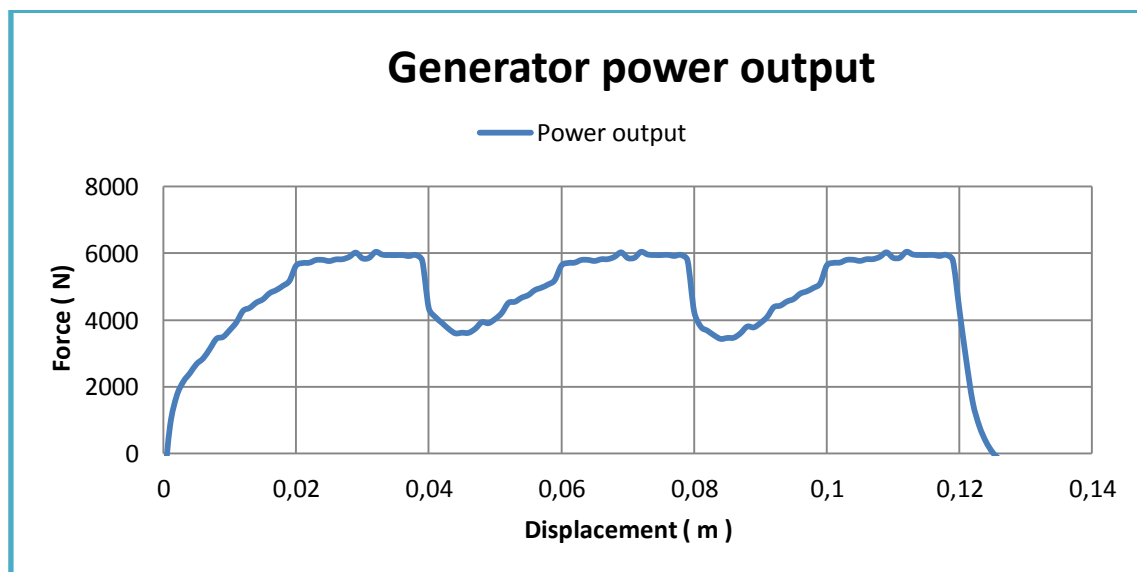
Switch position (Phase C): 0,080(ON) → 0,140(OFF)

(The surplus 0,02m on phase C overlaps Phase A on next step)

As seen in the last graph the smoothness is so much improved but at performance cost of:



Statistic 25: Average resistive losses = 857,20 W (power input = mechanical power)

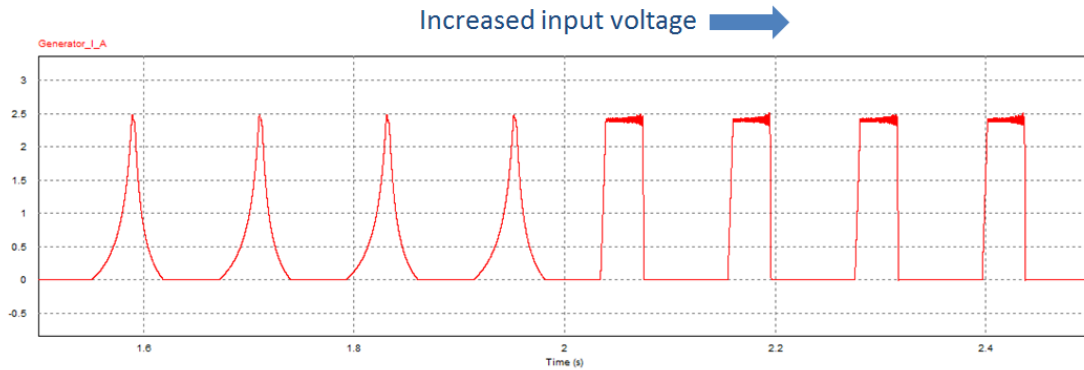


Statistic 26: Average power output = 5067,21 W

$$\eta = \frac{\text{Average power output}}{\text{Average power input}} = \frac{5067,21}{5924,41} = 0,8553 \rightarrow \mathbf{85,53 \%}$$

In order to increase the generator smoothness motion the performance is 5% decreased, but it is an acceptable value due the important factor improved.

Due the transitory time on an electrical circuit with coils on it, a study must be done to determine the correct voltage in order to reach a correct current working time on the coils. On the next graph it is possible to see how a different voltage on the power supply affects the steady time of the coils.



Statistic 27: Coil current waveform with a voltage increase

As seen in the previous graph, when the voltage increases the transitory time on the coils decreases and the steady current is reached before.

But the voltage is a constant value on the DC bus determined by the inverter working voltage, situated around 800V.

For that reason the voltage cannot be modified, but the generator can be adjusted to work on lower voltages reducing the number of turns on each coil and increasing the current and the wires cross section as well. With this adjustment we obtain the same generator specs and operation but at a lower voltage and thanks to it, it is possible to virtually increase the power supply voltage reducing the generator needed voltage.

$$I = \frac{V}{R} \left(1 - e^{-t \cdot \frac{R}{L}} \right)$$

As seen in the last equation, when increasing the V or reducing the R,L decreases the steady time. In the initial conditions to reach the operation current value (2,4 A) at 800V it will take a steady time of:

$$2,4 = \frac{800}{99,21} \left(1 - e^{-t \cdot \frac{99,21}{79,16}} \right) \rightarrow t = 0,2819 \text{ s}$$

But the available time (at standard working conditions) on a phase sequence is only 0,06s and this time includes three stages on it, the rising current, the steady and the decreasing time, for that reason for a proper operation the minimum transitory time must be situated at a third part of it, at a 0,02s of maximum.

$$\text{Times slower} = \frac{0,2819}{0,02} = 14,095$$

It means that the actual working conditions are 14 times slower than needed and must be increased up to this time to get a correct working operation, but for ensure even more optimal working conditions this value will be increased up to 30 times. So:

$$\text{Coil turns} = \frac{\text{Initial turns}}{30} = \frac{636}{30} = 21,20 \rightarrow 20 \text{ turns}$$

The new current must be adjusted to the new scenario in a proportional way:

$$Fm = \text{Current} * \text{turns} = \text{New current} * \text{new turns}$$

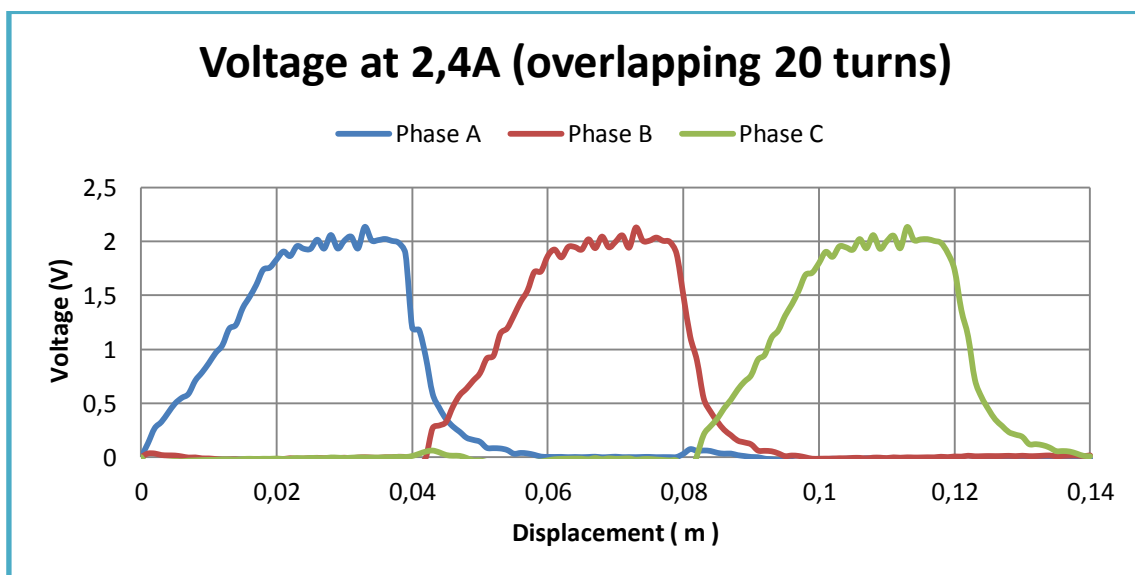
$$\frac{\text{New turns}}{\text{Turns}} = \frac{\text{Current}}{\text{New current}} \rightarrow \frac{20}{636} = \frac{2,4}{\text{New current}} \rightarrow 76,32 \text{ A}$$

The wire's cross section must be increased to:

$$\frac{\text{Current}}{\text{Cross section}} = \frac{\text{New current}}{\text{New cross section}} \rightarrow \frac{2,4}{0,001} = \frac{76,32}{\text{New cross sect.}} \rightarrow 0,0318 \text{ m}^2$$

Wires of 31,80 mm² will be used instead of the old ones of 1mm² to maintain the same current density and losses.

The output generator voltage by phase coil turn under standard conditions will be:



Statistic 28: Average voltage output by coil turn = 1,0516 V -> total phase average output = 84,13 V

Mechanical adjustment to work on the entire cycle motion: not just only in the up wave motion, so it is necessary a capable device to store half of the up motion energy. There are so many options (spring, pneumatic system with a reservoir, hydraulic system with a pressure accumulator...), but by the simplicity, price and reliability a regular coil will be used trying to implement it at the most constant force possible over the motion. The already implemented spring to maintain the wire tight will be improved to sustain the translator weight and deliver the needed storing force too.

It implies improving the returning spring by 5 in force, weight and price over the previous calculations.

Final generator specs:

- **Translator length** = 960 mm (two sections of 48mm each)
- **Stator length:** 2880 mm (six sections of 48mm each)
- **Air gap:** 1 mm (based on manufacturing technology)

- **Translator teeth width:** 40 mm
- **Translator teeth height:** 40 mm
- **Translator yoke height:** 60 mm
- **Translator coil slots:** $20 \times 40 \text{ mm} = 800 \text{ mm}^2$

- **Stator teeth width:** 40 mm
- **Stator teeth height:** 20 mm
- **Stator yoke height:** 32 mm

- **Generator mass:** 2059,82 kg (782,72kg related to the translator)
- **Generator expected output:** About 5000 W
- **Generator losses:** 857,20 W (average)
- **Generator performance:** 85,53 %
- **Generator DC BUS voltage:** 800 V
- **Generator Phase current:** 76,32 A
- **Generator Phase resistance:** 0,09811 Ω
- **Generator Phase induction range:** 0,07828 to 0,01046 H
- **Generator phase coil turns:** 20 (4 coils on each phase)
- **Generator coil wire:** Square type with 31,80 mm^2 of cross section

3.3 Generator thermic design

Simulation setup:

- Copper heat generation: As the phases (and losses) will be switching continuously, the losses will be distributed among all copper volume (obtained from simulation) to simulate a real working condition with the losses distributed among the translator length. It will be calculated on two different scenarios, without overlapping and with overlapping and checking if the translator is capable to dissipate the losses on each one.

$$Copper_{heat\ generation} = \frac{losses}{copper\ volume} \text{ (no overlapping)}$$

$$Copper_{heat\ generation} = \frac{620}{0,02171} = 28558,27\ W/m^3$$

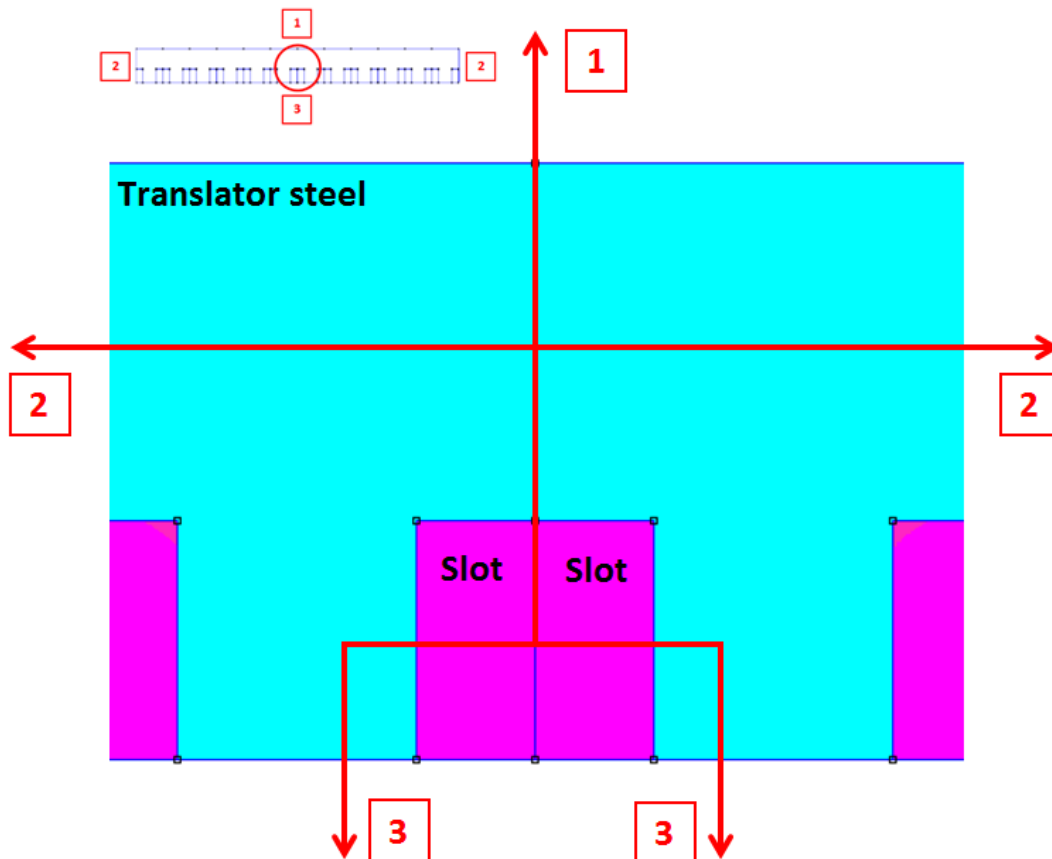
$$Copper_{heat\ generation} = \frac{losses}{copper\ volume} \text{ (overlapping)}$$

$$Copper_{heat\ generation} = \frac{857,20}{0,02171} = 39484,11\ W/m^3$$

- As insulation between the copper wires and the steel of the translator a thin layer of Kapton will be embed between the two materials. The voltage potential between the copper and the steel in regular conditions never will exceed the 1200V but to increase the durability a factor of 8 will be used ensuring a capability of 10000V insulation between materials. A 0,050mm layer of Kapton will be used (Thermal conductivity = 0,12W/m*K)
- As starting point natural convection will be considered between the translator outside and the inner air of the generator (Thermal convection = 8W/m*K) if is necessary more dissipation the air can be forced to increase the thermal convection or can be added cooling fins on the translator to increase the dissipation surface.
- The inner generator air will be supposed to 20°C (but in real conditions always will be lower thanks to the water lows temperatures) and the maximum wires temperature to protect the insulator enamel will be 140°C
- The external enclosure thermic properties will be ignored because it has a huge surface on water contact ensuring a great heat transfer).

Like in the magnetic design, we can convert the thermic circuit into an electrical equivalent circuit to understand it easier and provide a better workspace where make the thermic calculations.

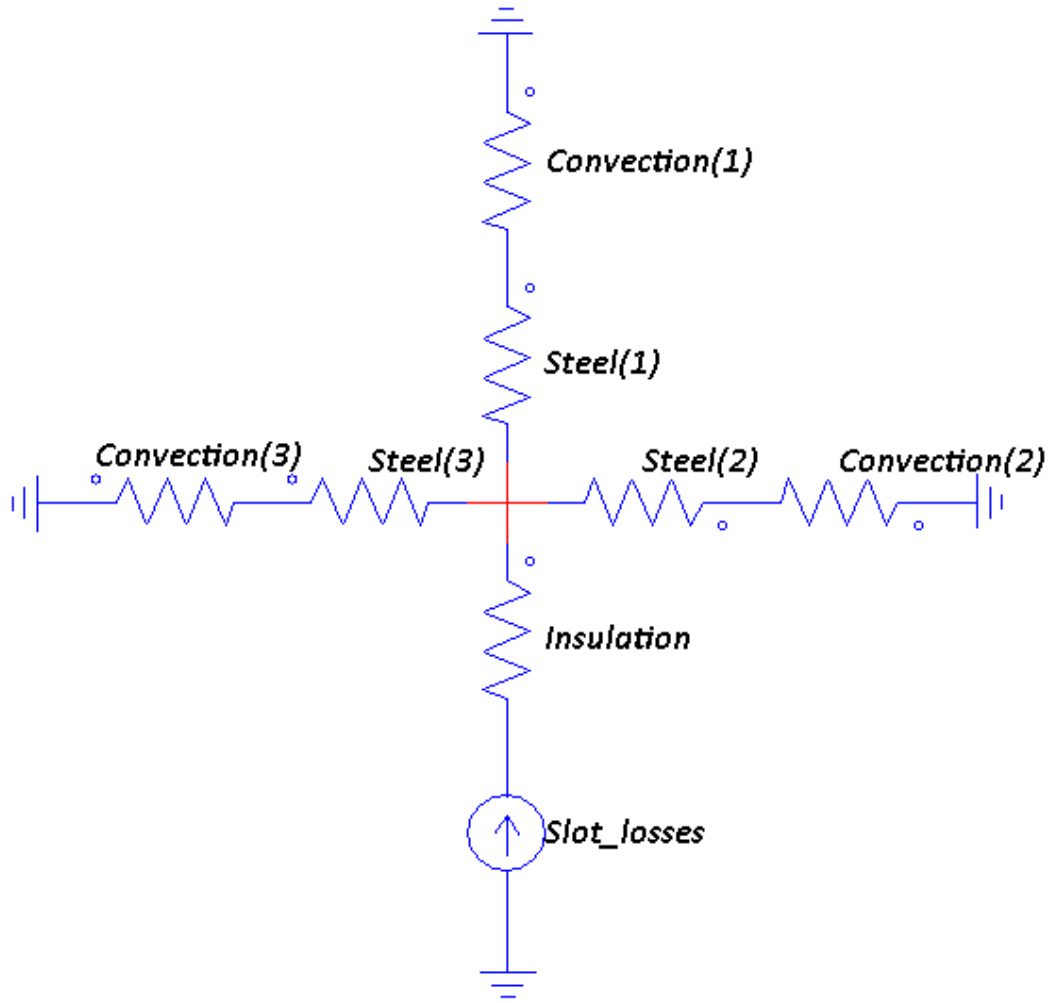
Only one pair of slots will be taken into account to simplify the calculations and then it will be extrapolated to the entire translator. The small side's thermic convection (2) will be simplified adding this surface into the external big one (1) proportionally making this way the translator capable to be simulated on a small part of it.



Picture 20: Thermic flux diagram showing thermic evacuation paths

Then the thermic circuit can be drawn with the next parameters:

- Current = thermic flow (W) → From simulation
- Voltage = Temperature increase (K) → Unknown
- Resistance = Thermic resistance (K/W) → Calculated



Picture 21: Thermic equivalent circuit

Thermic resistance calculation:

$$Insulation_{resistance} = \frac{Thickness}{\lambda * surface} = \frac{0,00005}{0,12 * 0,08 * (2 * \pi * 0,1)} = 0,008289 \text{ K/W}$$

$$Steel(1 + 2)_{resistance} = \frac{Thickness}{\lambda * surface} = \frac{0,06}{43 * (0,08 + 0,01) * (2 * \pi * 0,13)} \\ = 0,01898 \text{ K/W}$$

$$Convection(1 + 2)_{resistance} = \frac{1}{\alpha * surface} \\ = \frac{1}{8 * ((0,08 * 2 * \pi * 0,1) + (0,01 * 2 * \pi * 0,13))} = 2,1392 \text{ K/W}$$

$$Steel(3)_{resistance} = \frac{Thickness}{\lambda * surface} = \frac{0,04}{43 * 0,02 * (2 * \pi * 0,2) * 2} = 0,01851 K/W$$

$$Convection(3)_{resistance} = \frac{1}{\alpha * surface} = \frac{1}{8 * 0,02 * (2 * \pi * 0,2 * 2)} \\ = 2,4868 K/W$$

$$Resistance(1 + 2) = steel(1 + 2) + convection(1 + 2) = 2,1582 K/W$$

$$Resistance(3) = steel(3) + convection(3) = 2,5053 K/W$$

$$Resistance_{equivalent(1,2,3)} = \frac{1}{\frac{1}{Resistance(1 + 2)} + \frac{1}{Resistance(3)}} = 1,1594 K/W$$

$$Total resistance = Insulation + Requivalemt(1,2,3) = 0,008289 + 1,1594 \\ = 1,1677 K/W$$

$$Slot \Delta temperature = Slot losses * Total resistance (K)$$

$$(No overlapping)Slot_{losses} = \frac{Total losses}{Pair slots} = \frac{620}{12} = 51,67 W$$

$$(Overlapping)Slot_{losses} = \frac{Total losses}{Pair slots} = \frac{857,2}{12} = 71,43 W$$

Without overlapping slot (wires) max temperature:

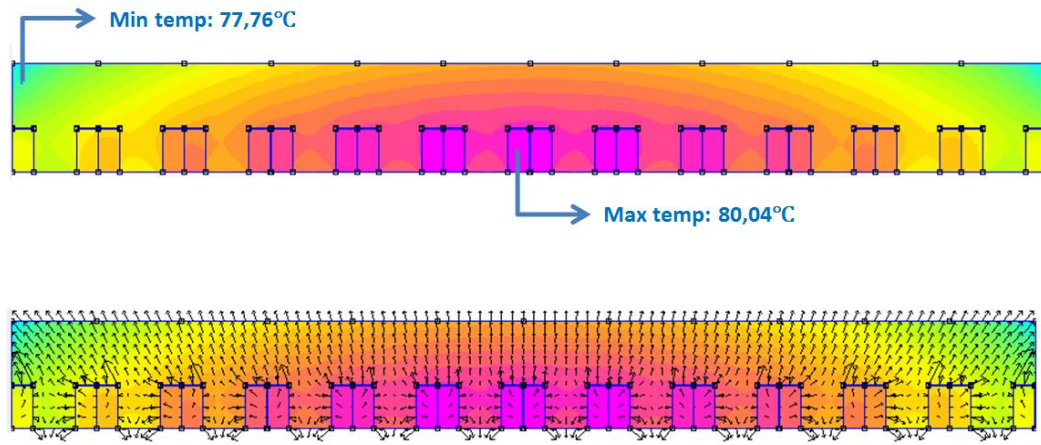
$$\Delta Temp = 51,67 * 1,1677 = 60,34 K$$

$$Max temp = \Delta Temp + air temp = 60,34 + 20 = 80,34 ^\circ C$$

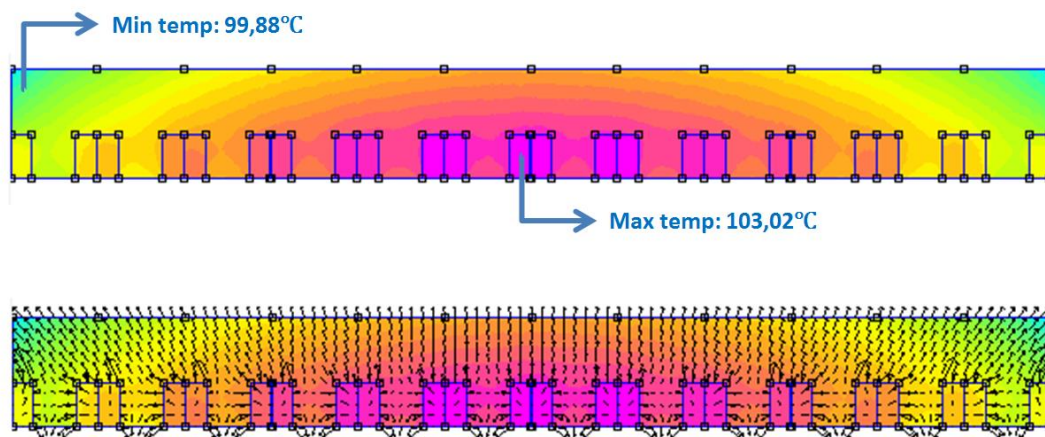
With overlapping slot (wires) max temperature:

$$\Delta Temp = 71,43 * 1,1677 = 83,41 K$$

$$Max temp = \Delta Temp + air temp = 83,41 + 20 = 103,41 ^\circ C$$



Picture 22: Thermic gradient and thermic flux on no overlapping setup (Max $\Delta T=60,04$ K)

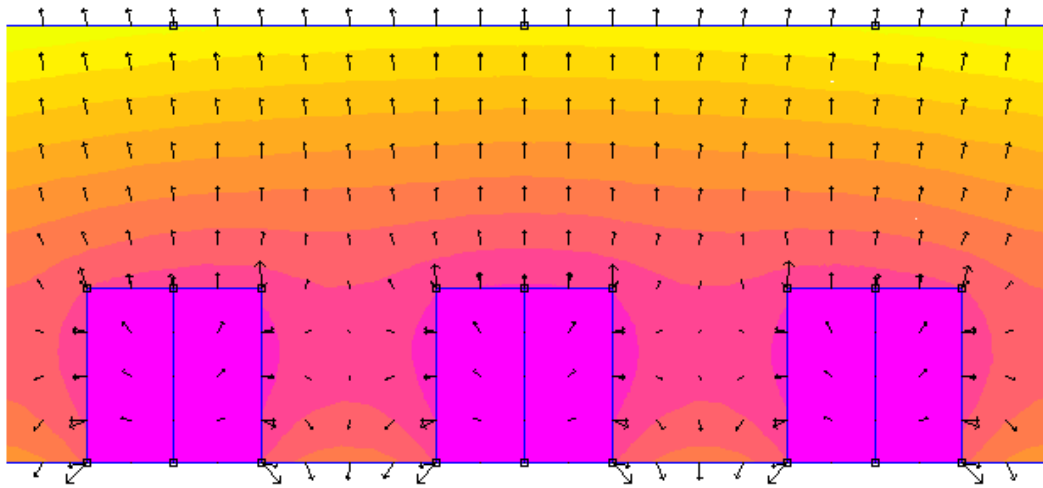


Picture 23: Thermic gradient and thermic flux on overlapping setup (Max $\Delta T=83,02$ K)

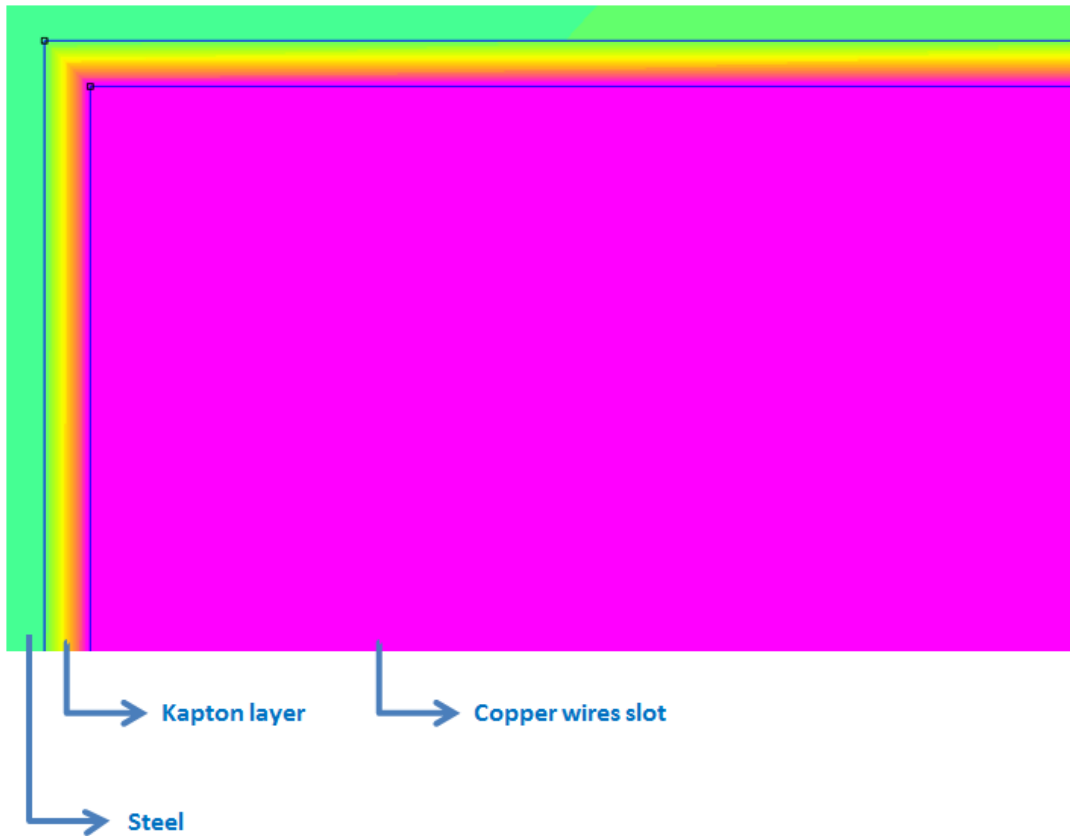
As simulations shows, the thermic design is correct, and there is no need to improve the thermic flux or convection because the basic design without fins on the external surface and natural convection is just working ensuring a maximum temperature of:

- Without overlapping max temperature: 80,04°C
- Overlapping max temperature: 103,02°C

Which are far to the maximum 140°C of the copper enameled wires used.



Picture 24: Central zone detail

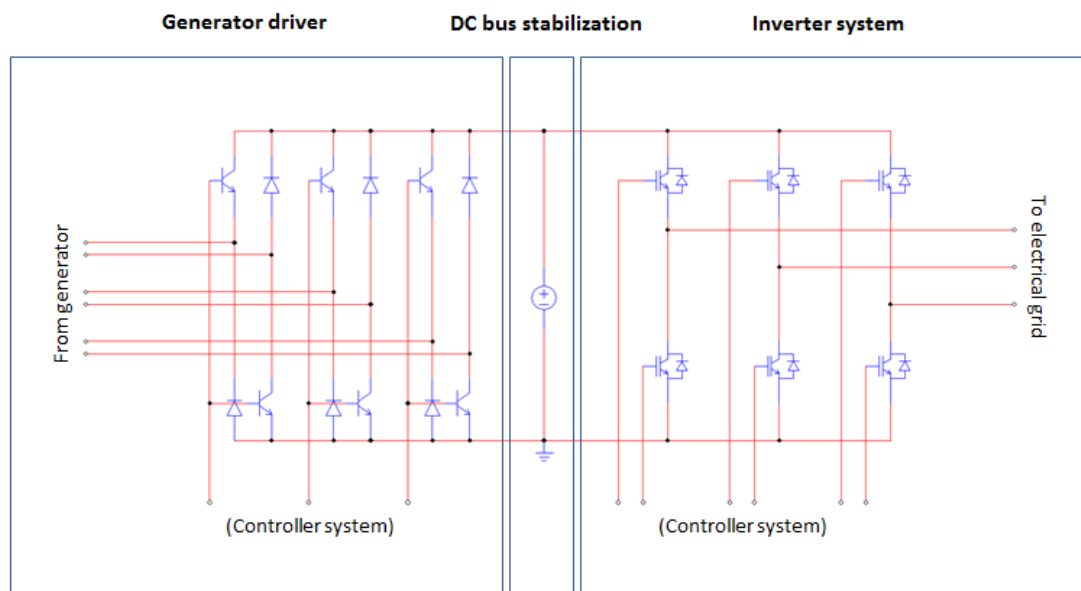


Picture 25: Wires slot and insulator (Kapton) detail

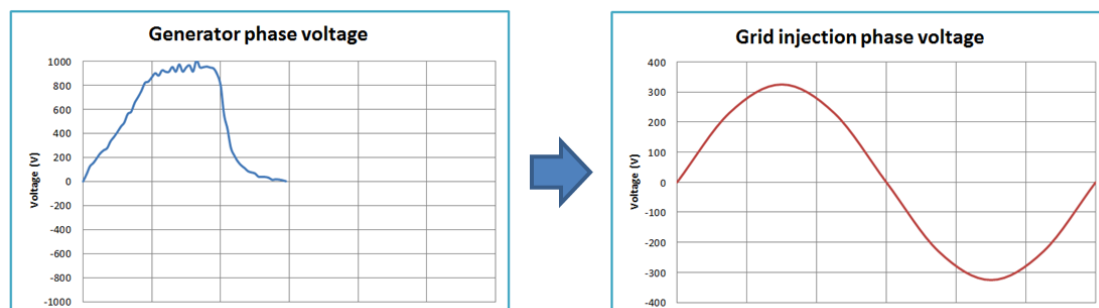
3.4 Generator electronic design

The generator electronics system is based on 3 primary parts:

- **Generator driver:** Will be in charge of controlling the activation and deactivation phases on the translator. Will handle too the current system ensuring that every active phase receives the calculated current amount at all time. Finally will perform the generation current extraction to the DC bus.
- **DC bus stabilization:** As the power will come with ripple at different times, it will guarantee that on the DC bus always will be the correct voltage value for the inverter, storing it and stabilizing it.
- **Inverter system:** Will be in charge of converting the direct current (DC) into alternating current (AC) injecting it on the electrical grid delivering the generated electrical power to the final consumers.



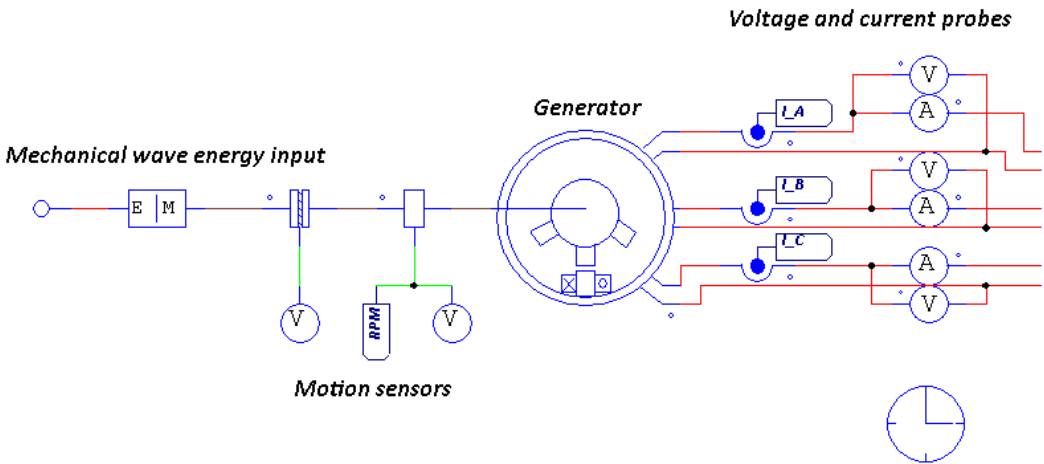
Circuit 1: Typical electronic system to inject electrical power generated into the grid



Picture 26: Phase voltage transformation on the electronic system

The final electronic circuit is composed by the next parts:

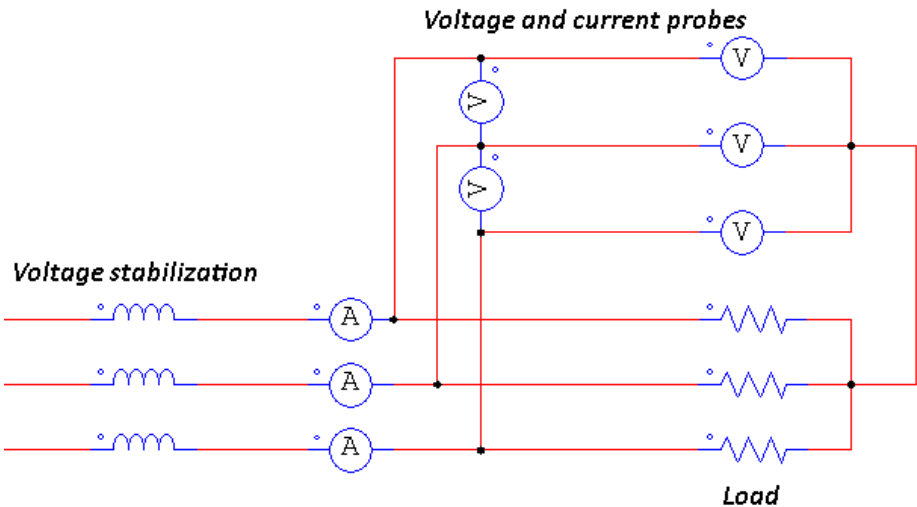
Generator and mechanical input simulation:



Circuit 2: Generator and mechanical energy circuit

The mechanical energy input is simulated with an electrical-mechanical interface that sets the mechanical speed at standard conditions (1m/s) on reverse generator natural motion and opposing the generator force to produce electricity on it. All the system is configured on rotatory way due to the software limitation (PSIM) but all the linear values are accurately translated to rotatory values to simulate properly the system.

Grid simulation:



Circuit 3:Grid simulation circuit

The electrical grid connection is simulated with a load according to the maximum generator output power, and a voltage waveform correction is performed adding one inductance on each phase to avoid the output voltage ripple. The grid is simulated under the standard conditions of $230V_{\text{phase rms}}$, $400V_{\text{line rms}}$, at 50hz frequency with 5000W of output power.

PWM output voltage at maximum modulation:

$$U_{LL \text{ rms}} = 0,612 * m * DC \text{ BUS}$$

$$U_{LL \text{ rms}} = 0,612 * 1 * 800 = 489,60 \text{ V} \rightarrow 282,67 \text{ V}_{\text{phase rms}}$$

Resistance and inductance calculation to obtain 5000W power consumption:

$$U = I * R \rightarrow 230 = I * R$$

$$P = I^2 * R \rightarrow \frac{5000}{3} = I^2 * R$$

From the previous equations is obtained:

$$1666,67 = I^2 * \frac{230}{I} \rightarrow I = 7,25 \text{ A}$$

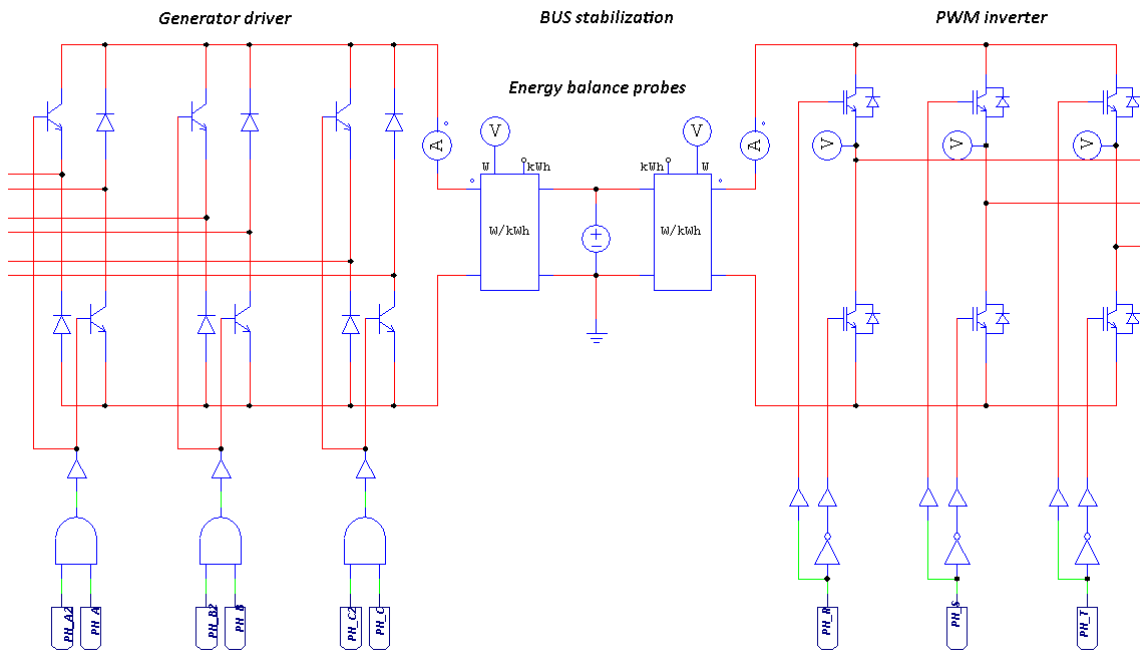
$$R = \frac{230}{I} = \frac{230}{7,25} = 31,72 \Omega$$

To find the stabilizing inductance:

$$I = \frac{U}{Z} \rightarrow 7,25 = \frac{282,67}{\sqrt{31,72^2 + X^2}} \rightarrow X = 22,67 \text{ j}\Omega$$

$$L = \frac{X}{2 * \pi * f} = \frac{22,67}{2 * \pi * 50} = 0,07216 \text{ H}$$

Generator driver, DC BUS and inverter:



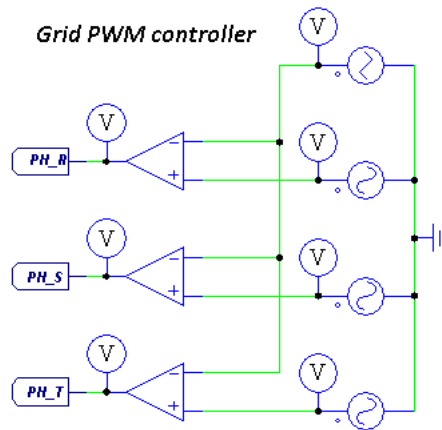
Circuit 4: Generator driver, DC BUS and inverter circuit

The generator driver operation is done by 6 electronically commanded switches that are capable to feed each generator phase with a pulse modulation at the desired voltage between -800V to +800V range. An electronic circuit commands it to enable or disable each phase and feed them at the correct current value.

In the same way the inverter is designed under the electronic pulse modulation capable to feed each phase at the standard voltage output.

The DC BUS stabilization (Adjusted to 800V) is represented by a battery system that stores and equilibrates the total amount of energy balance between the input (generator) and the output (inverter) and provides the initial energy to start the generator operation. There are two wattmeters capable to read the actual balance situation and modify the output if the generation is lower than expected.

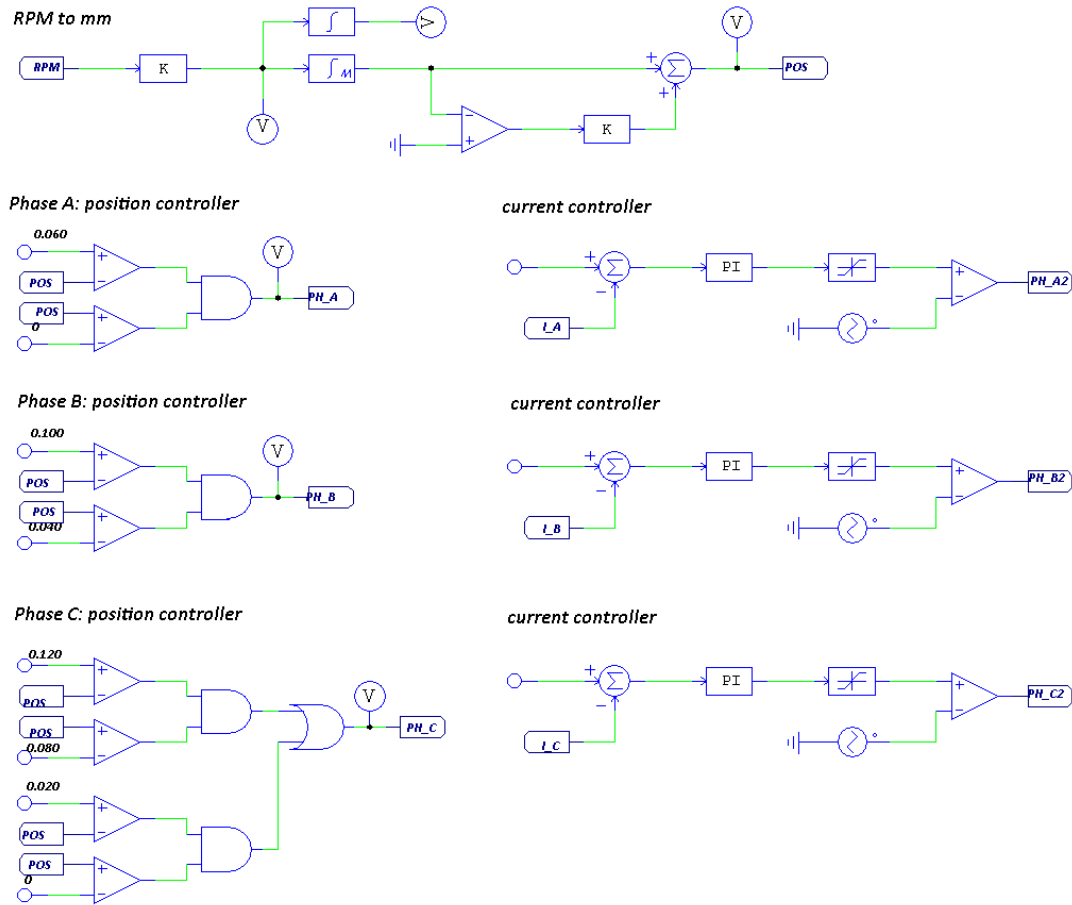
Inverter controller:



Circuit 5: Circuit of the PWM controller

The controller is done by a regular PWM controller. It constantly reads signal from a reference voltage source with a correct waveform and phase angle offset and applies it to the PWM switches transforming this ideal waveform into a real waveform made by multiples voltage pulses. This modulation method has some limitations, as the relative low voltage output at maximum modulation due the harmonic load on the real output waveform, but is a simple and so much used method to obtain a triphasic AC output from a DC source.

Generator driver controller:

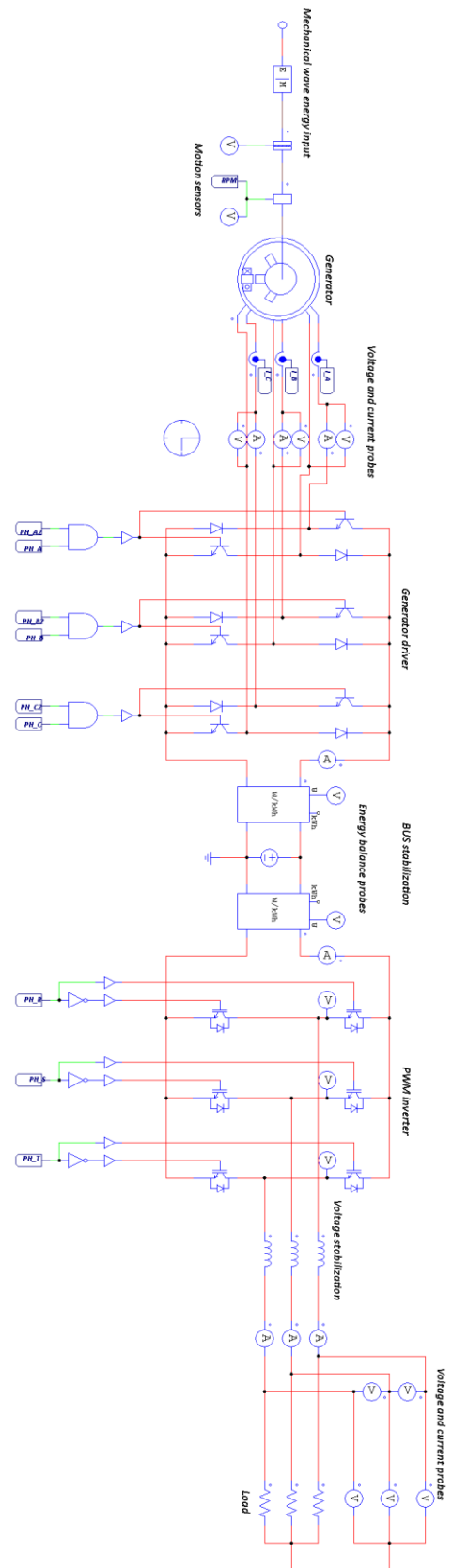


Circuit 6: Circuit of the generator driver controller

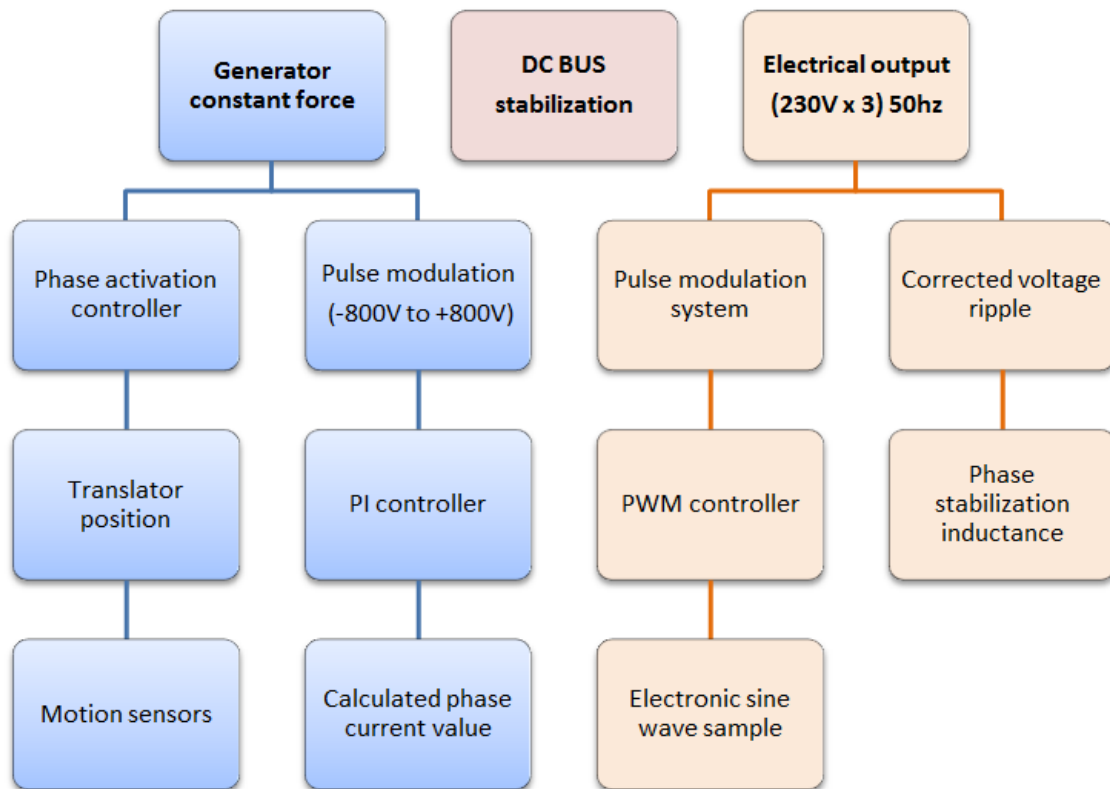
The upper module converts the rotatory RPM reads to lineal displacement integrating it. There are two values, the absolute position and the relative one corresponding to a cycle of 120mm (90° on the equivalent rotatory machine).

The position controllers activate or deactivate each phase when it is at the correct working position and it is possible to control overlapping with this setting. The lowest module is used to obtain the next cycle overlapping of the C phase.

The current control is done by a PI in charge of guarantee, on the generator phases, the correct current value at every moment, changing on it the pulse modulation in order to increase or decrease the voltage applied at this phase. With this control it is possible to maintain the generator force constant and extract the generator energy produced modifying the phase voltage.

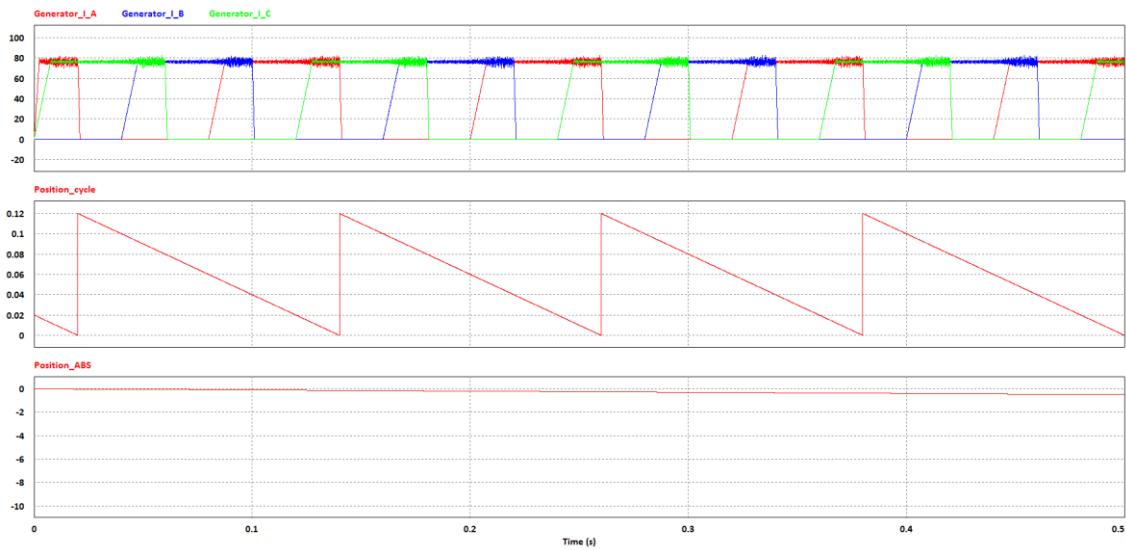


Circuit 7:Final electronic circuit design



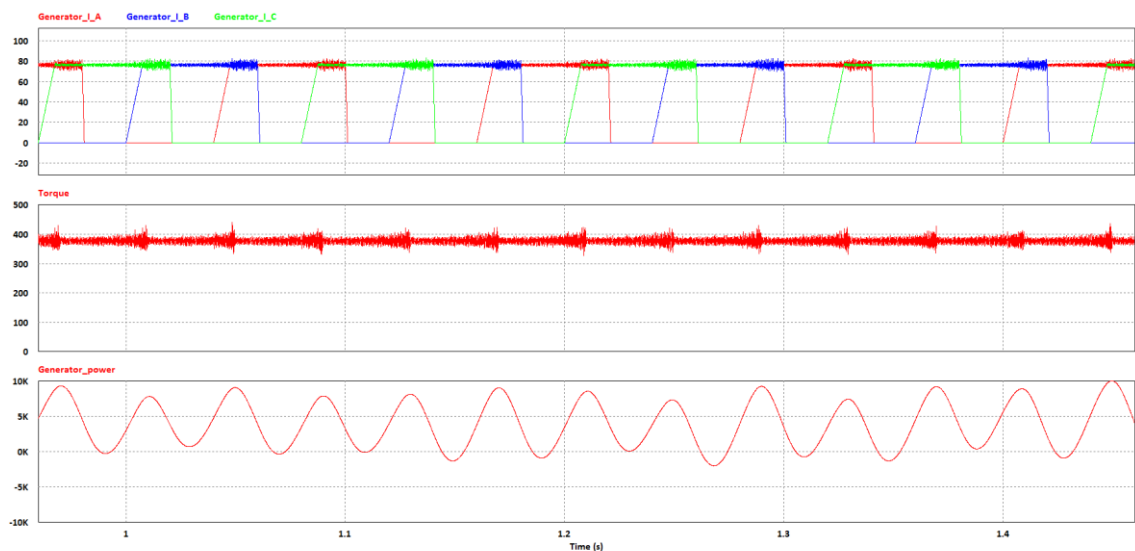
Picture 27: Electronic system scheme

Circuit simulation:



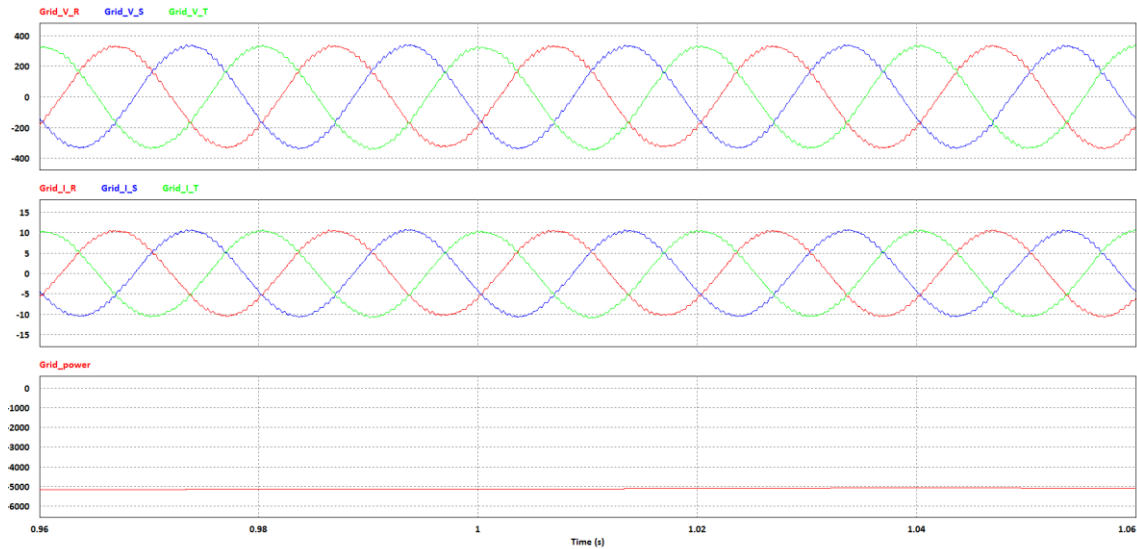
Statistic 29: Generator operation simulation

The phase controller operation is shown on the previous graph. It is possible to see how it enables and disables each phase at the correct position provided by the linear relative position with a 120mm range and how it overlaps the phases as calculated on the section 3.2 to stabilize more the force done by the generator. The last value displays the absolute position of the generator on a decreasing way because is at reversing motion with the mechanical energy opposing the natural generator force.



Statistic 30: Generator force and power output simulation

The generator force (represented by rotatory torque) is maintained almost constant meanwhile the generator power oscillates due the variable voltage output calculated in section 3.2 but this is not a problem thanks to the stabilization at DC BUS.



Statistic 31: Simulation on the grid side

Device's output values, displaying the phase voltage on the load, the phase current and the total grid power output stabilized at the expected value. As expected the stabilization inductance at the inverter output transforms the voltage pulse waveform into a correct sinusoidal waveform at the load side (where the probes are located).

Finally the output simulation values can be checked as corrects into the next table validating the electronic circuit design:

RMS Value		
Time	From	9.5998771e-001
Time	To	1.0600255e+000
<hr/>		
Grid_V_R		2.3359963e+002
Grid_V_S		2.3425330e+002
Grid_V_T		2.3503888e+002
<hr/>		
Grid_I_R		7.3644271e+000
Grid_I_S		7.3850348e+000
Grid_I_T		7.4098009e+000
<hr/>		
Grid_power		5.1220048e+003

Statistic 32: Output RMS values

4 Final set plans, specs and price

Device total buoyancy:

$$\text{Buoyancy} = \text{body volume} * \text{water density} * \text{gravity (N)}$$

$$\text{Body volume} = \frac{1}{2} \text{ upper sphere} + \text{body cylinder} + \frac{1}{2} \text{ bottom sphere (m}^3\text{)}$$

$$\text{Sphere volume} = \frac{4}{3} * \pi * r^3 = \frac{4}{3} * \pi * 0,75^3 = 1,7671 \text{ m}^3$$

$$\text{Cylinder} = \pi * r^2 * h = \pi * 0,75^2 * 3 = 5,3014 \text{ m}^3$$

$$\text{Buoyancy} = (1,7671 + 5,3014) * 1030 * 9,8 = 71349,44 \text{ N}$$

Device weight:

$$\text{Weight} = \text{device mass} * \text{gravity (N)}$$

$$\text{Device mass} = \text{enclosure} + \text{generator} + \text{wire} + \text{others (kg)}$$

$$\text{Enclosure mass} = 2039,45 \text{ kg (calculated on section 2.3)}$$

$$\text{Generator mass} = 2059,82 \text{ kg (calculated on section 3.2)}$$

$$\text{Wire mass (max)} = 240,16 \text{ kg (calculated on section 2.3)}$$

$$\text{Others} = \text{Spring} + \text{security light} + \text{electronics} + \text{internal wires and mounts}$$

$$\text{Spring} = 35 * 5 = 175 \text{ kg (improved from section 2.3)}$$

$$\text{Security light} = 15,65 \text{ kg (calculated on section 2.3)}$$

$$\text{Electronics} = 50 \text{ kg (aprox)}$$

$$\text{Others (wires, mounts, rails, bearings ...) = increase up to 10\% final weight}$$

$$\text{Weight} = (2039,45 + 2059,82 + 240,15 + 175 + 15,65 + 50 + 10\%) * 9,8$$

$$\text{Device mass} = 5038,10 \text{ kg}$$

$$\text{Device weight} = 49373,15 \text{ N}$$

Generator forces:

Generator operation force = 5924,41 N (calculated on section 3.2)

Store energy for down motion = Generator operation force = 5924,41 N

Device acceleration needed = 0,6667 m/s² (calculated on section 2.1)

*Acceleration force = 0,6667 * 5038,10 = 3358,90 N*

Dedicated force on generation = 15207,72 N

Remaining buoyancy force = Buoyancy – weight (N)

Remaining buoyancy force = 71349,44 – 49373,15 = 21976,29 N

Buoyancy surplus force = 21976,29 – 15207,72 = 6768,57 N

*** This force surplus validates the project** calculations as correct and ensures a proper device operation. The surplus force adds room for further improvements that require more weight on the device and allow modifications on operation range. The surplus can be compensated filling the device with water to reach the desired amount of extra buoyancy.

Generator price:

(Volumes are obtained on section 3.2 with software calculation)

$$\text{Stator price} = \text{volume} * \text{density} * \text{price}$$

$$\text{Stator price} = 0,1627 * 7850 * 1 = 1277,12 \text{ €}$$

$$\text{Translator price} = \text{volume} * \text{density} * \text{price}$$

$$\text{Translator price} = 0,06876 * 7850 * 1 = 539,77 \text{ €}$$

$$\text{Copper price} = \text{volume} * \text{filling factor} * \text{density} * \text{price}$$

$$\text{Copper price} = 0,02171 * 0,8 * 8940 * 6,8 = 1055,84 \text{ €}$$

$$\text{Electronics} = 750 \text{ € (aprox)}$$

$$\text{Generator total price} = 3622,73 \text{ €}$$

Device price:

$$\text{Device price} = \text{gen.} + \text{enclosure} + \text{spring} + \text{light} + \text{wire} + \text{anchorage} + \text{others}$$

$$\text{Enclosure price} = 2039,45 \text{ € (calculated on section 2.3)}$$

$$\text{Light price} = 124,48 \text{ € (calculated on section 2.3)}$$

$$\text{Wire price (max)} = 350,06 \text{ € (calculated on section 2.3)}$$

$$\text{Seafloor anchorage price} = 136,51 \text{ € (calculated on section 2.3)}$$

$$\text{Spring price} = 30,87 * 5 = 154,35 \text{ € (improved from section 2.3)}$$

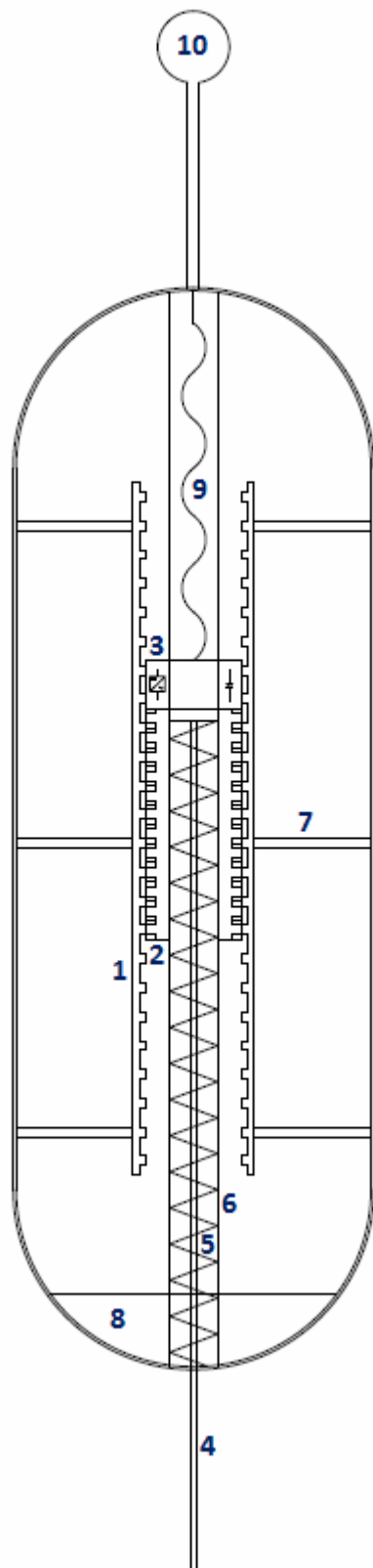
$$\text{Others (wires, mounts, rails, bearings ...)} = \text{increase up to 10\% final price}$$

$$\text{Device price} = 3622,73 + 2039,45 + 154,35 + 124,48 + 350,06 + 136,51 + 10\%$$

$$\text{Device price} = 7070,34 \text{ €}$$

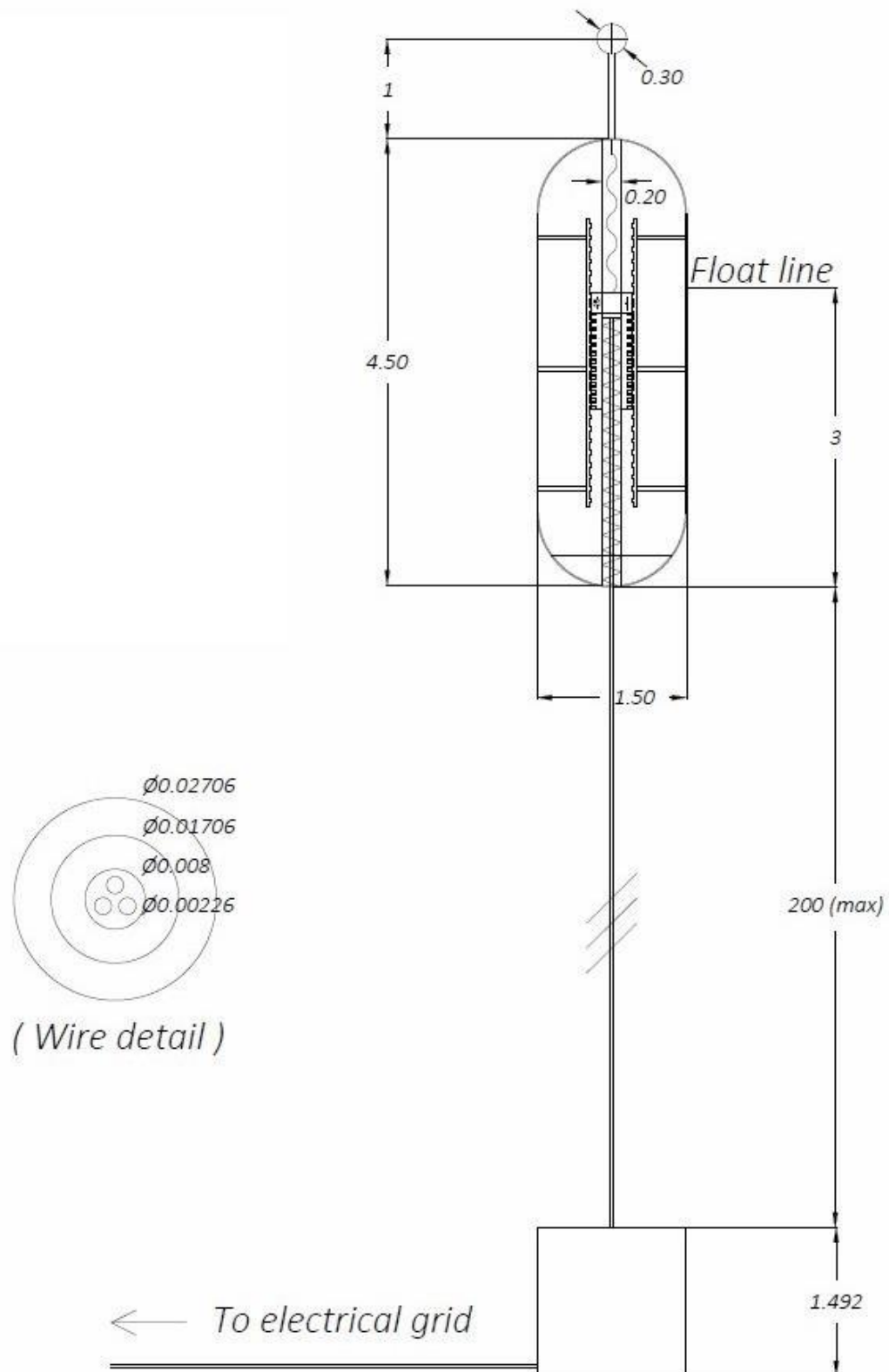
Final device specs and prices:

- **Device type** = Point absorber
- **Dimensions (L,W,H)** = 1,5m 1,5m 4,5m
- **Mass and weight** = 5038,10kg and 49373,15N
- **Device price** = 7070,34€
- **Generator type** = Linear switched reluctance
- **Output voltage** = Triphasic 400Vrms 50hz
- **Output power (under standard conditions)** = 5000W
- **Electricity production by year** = 43800kWh
- **Performance** = 85,53%
- **Max generator temperature** = 103,02°C (on translator)
- **Standard working conditions** = 3m wave at 6s period
- **Max pressure supported** = 50m water column (5bar)

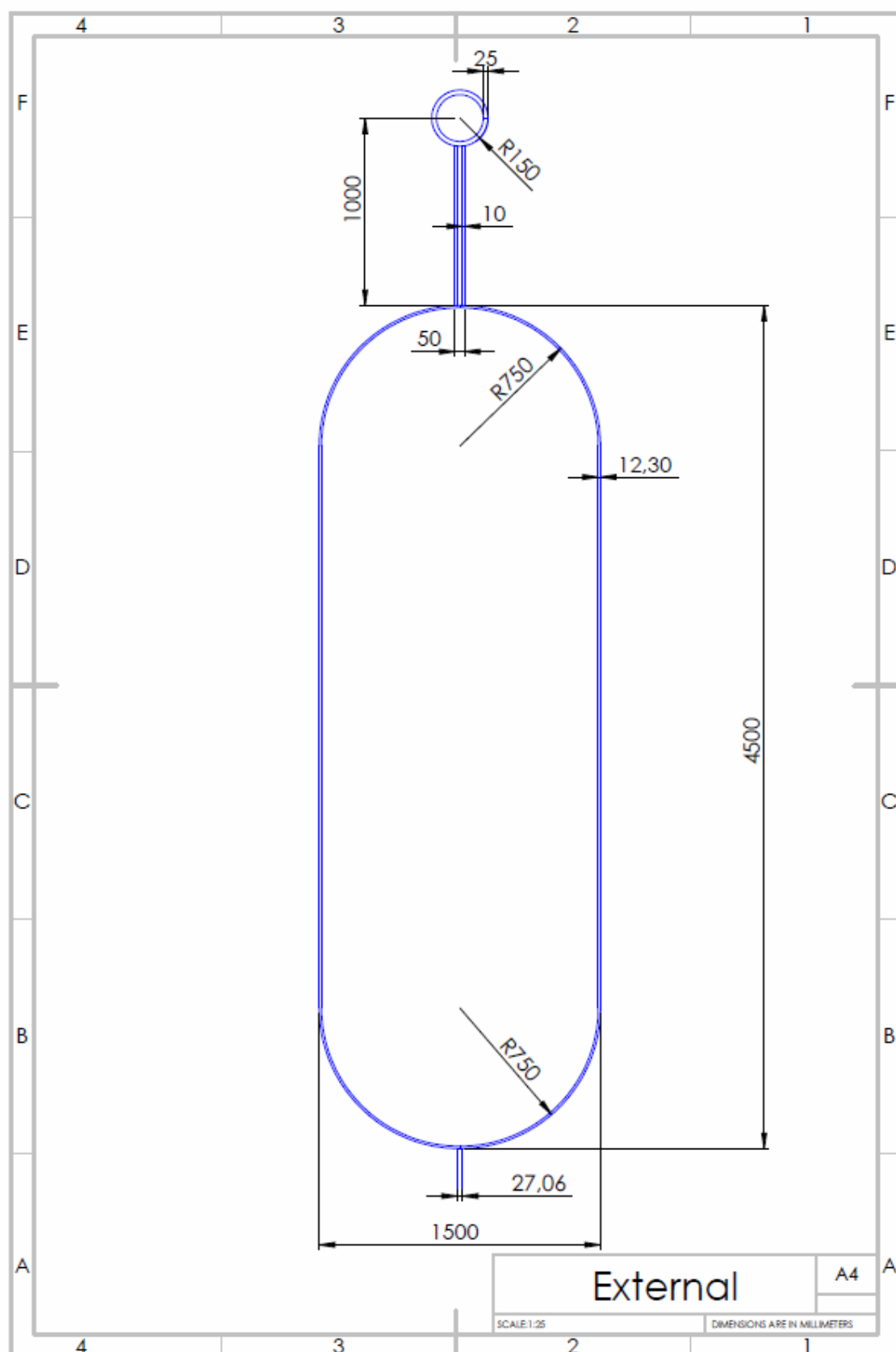


- 1) Stator
- 2) Translator
- 3) Electronics
- 4) Wire
- 5) Spring
- 6) Translator guide tube
- 7) Stator mountings
- 8) Balancing water
- 9) Light wire
- 10) Security light

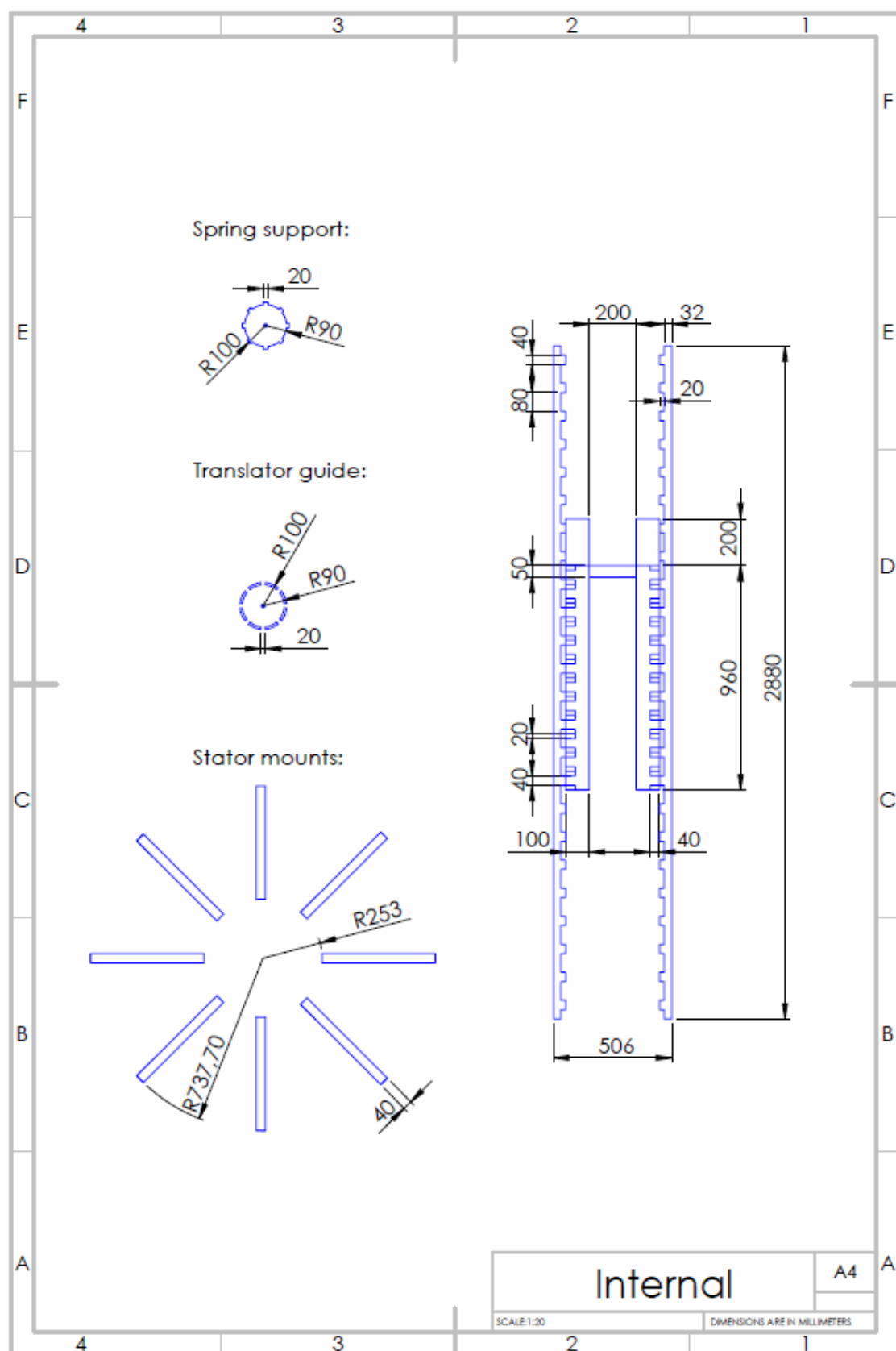
Drawing 25: Device elements description



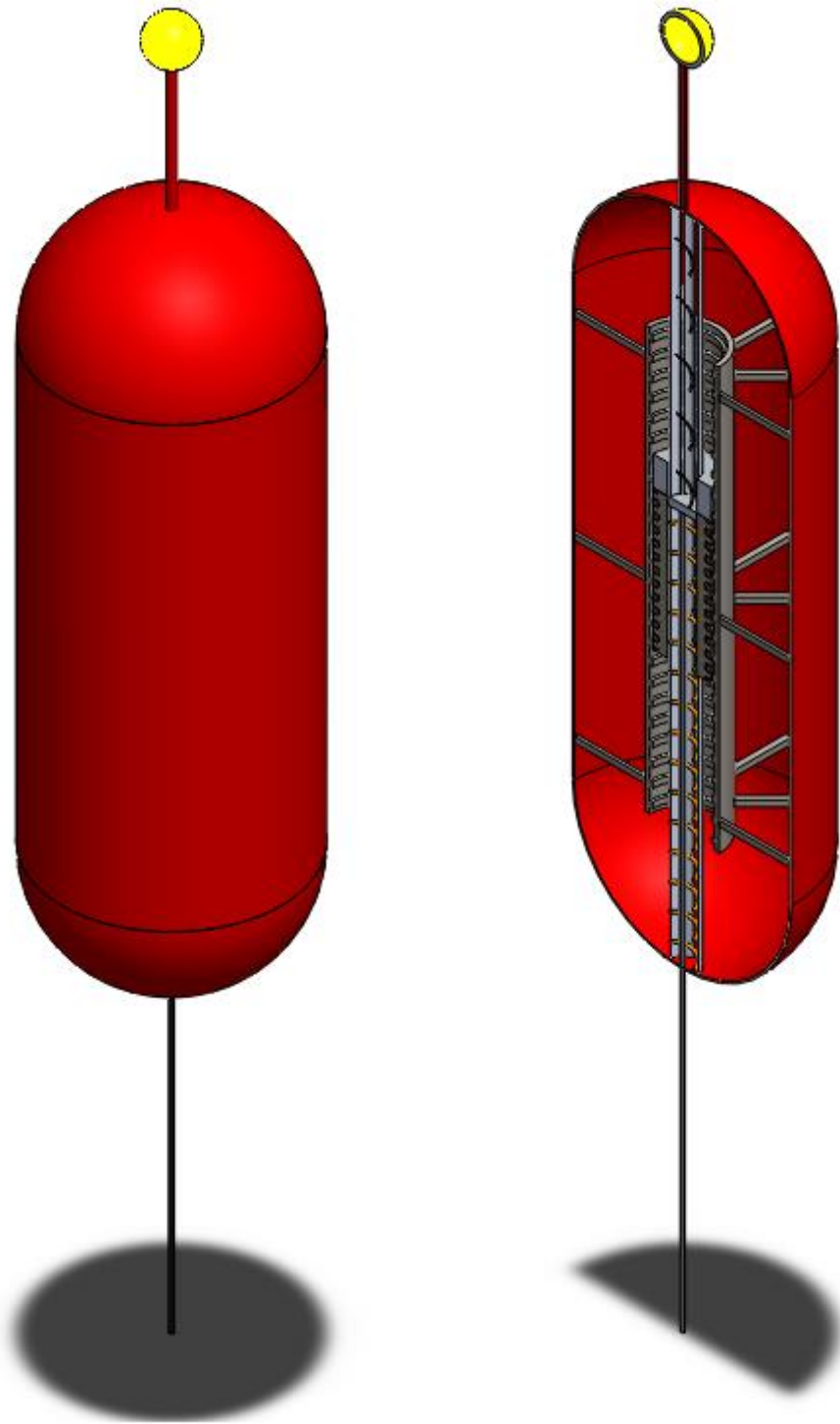
Drawing 26: Device main dimensions



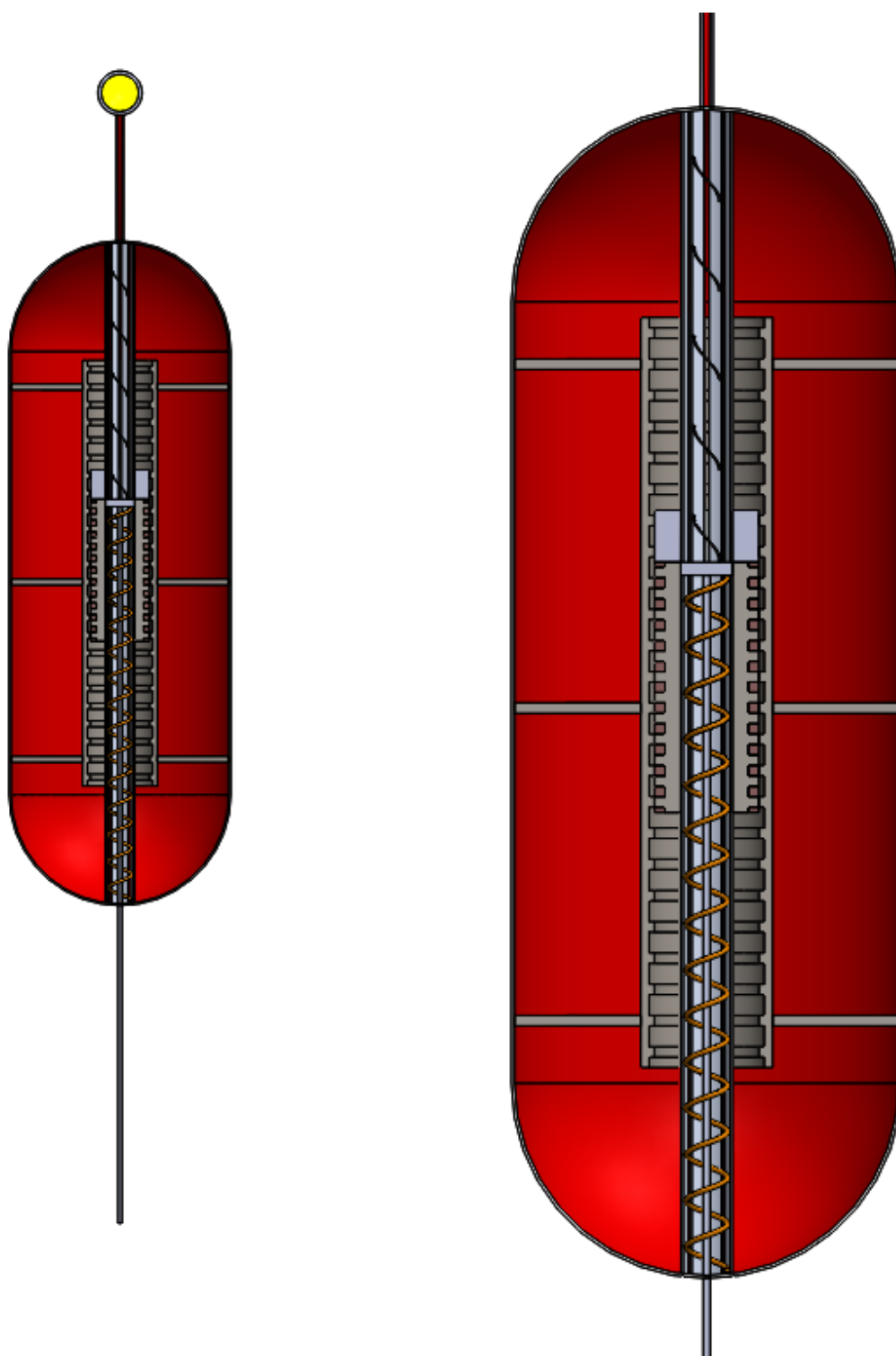
Drawing 27: Detailed external dimensions



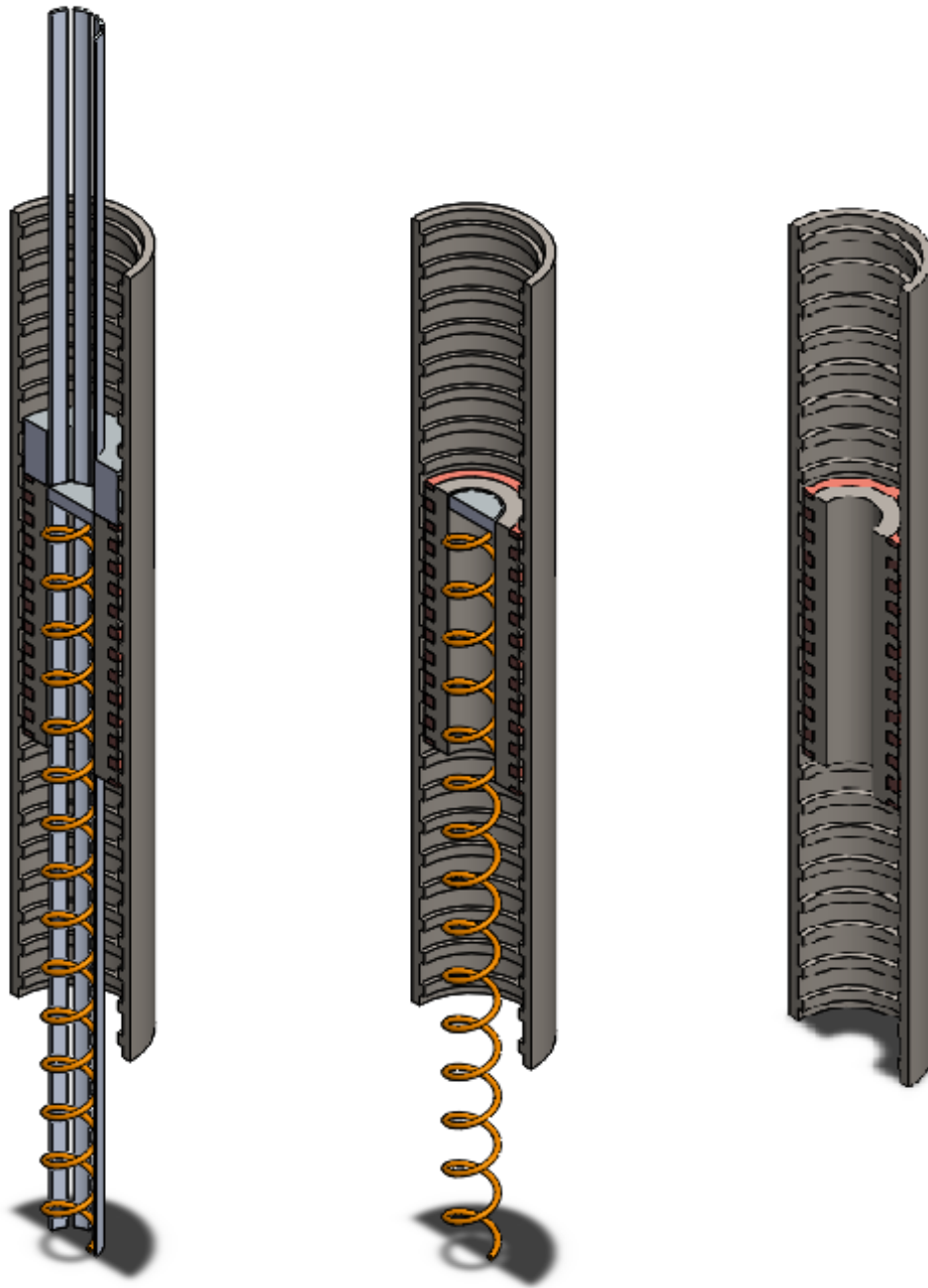
Drawing 28: Detailed internal dimensions (without spring)



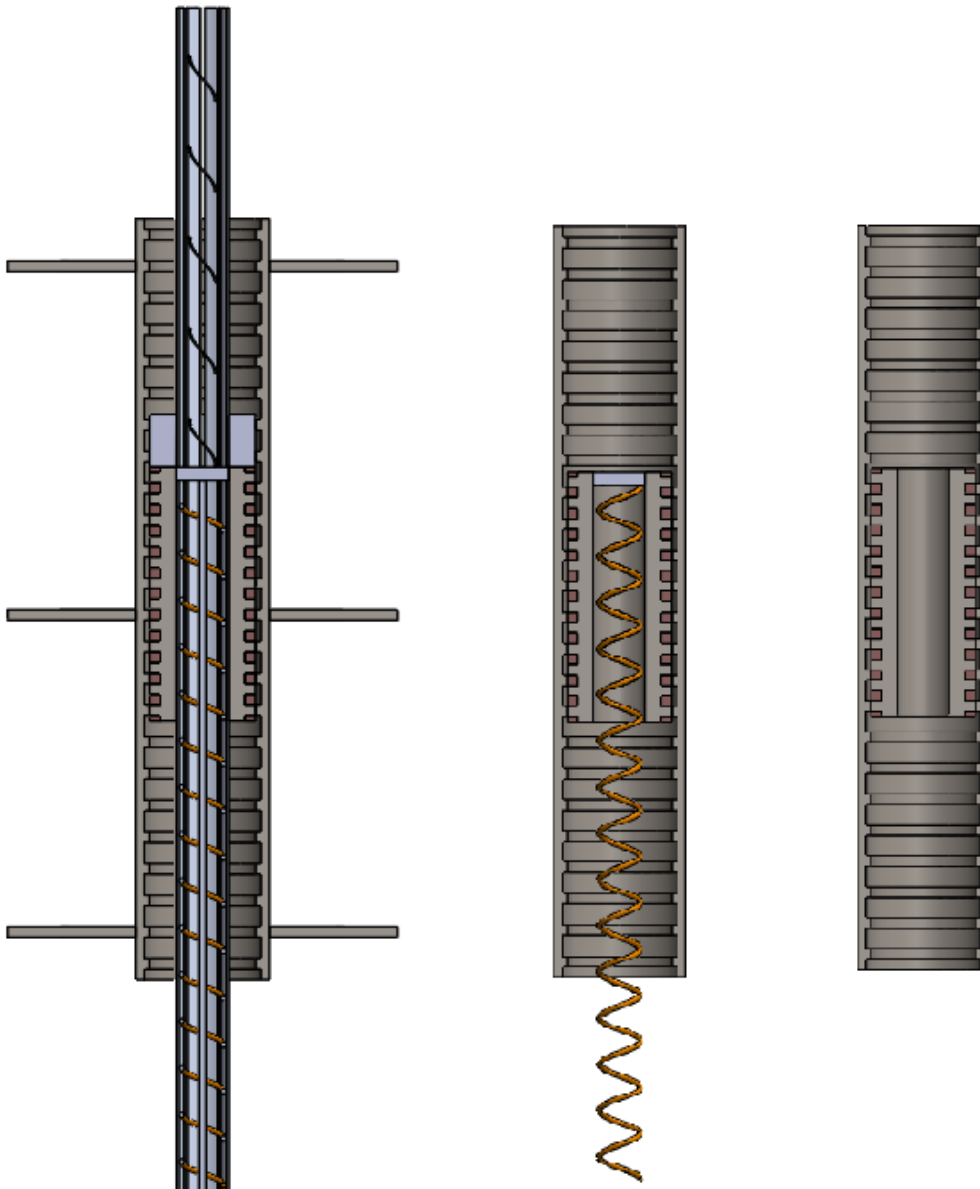
Picture 28: (3D rendering) external and inner cut view



Picture 29: (2D rendering) Device's cut showing the inner parts



Picture 30: (3D rendering) generator in detail with external accessories to basic components



Picture 31: (2D rendering) generator in detail with external accessories to basic components

5 Conclusions

As exposed in this project it is possible to build an electrical generator working over the ocean wave energy in a profitable way without compromising the device quality or reliability.

The device can work on two ways:

- As standalone on isolated places
- Connected to electrical grid

The most usual operating mode will be connected to the electrical grid discharging on it the renewable electricity generated, but is also possible to work alone on isolated places where there is not electrical connection available. Thanks to it, it is possible to deliver electrical energy on isolated coastal places, for example in small isolated villages or isolated research centers.

Nowadays even in the renewables field, the price and payback time is a key factor, for that reason on the entire project design the price has been supervised to obtain a profitable device and a real option to be built and deployed.

The final device price is around 7000€ at built cost and is capable to generate more than 5000W continuously. Taking into account a selling price of the electricity of 0,10€ kWh the generator is capable (under proper working conditions) to generate 43800kWh per year, it means an income of 4380€, and it makes a payback time less than two years.

Being rational, with a doubled device price (including external factors like transport, deployment, maintenance...) and halving the income due more realistic working conditions, this implies a payback time less than eight years and compared with other energy sources, that is an affordable device.

Also it is important the low device price, making it a good generation system for a small electrical companies seeking to invert on renewables energies or even for a private individuals or small collectives.

That is so important because this is the way in present times to boost a technology, making it affordable and capable to compete with the actually used ones, pursuing the global needed change to the renewables sources.

At this time the traditional electric motors and generators are changing into a new line based on permanent magnets and reluctance thanks to the stimulus coming from the electric car industry and renewables companies pursuing a change on this area to use the best possible motors and generators on their products that is why it is so important nowadays investing on this technologies to consequently help the environment improvement.

There is a need to increase the global knowledge on this area and implement this technology even more on engineering studies, bringing to future developers the tools to work on it.

This project is a collection of small projects linked between in the main project, making it modular and with lot development options. Concretely there are four important upgrading options that can improve significantly the generator performance:

- Implement a more accurate generation control over the buoyancy instead of a constant force. Thanks to it the device will be more adaptable to environment changes.
- Increment the generator motion travel to be employed on higher waves areas.
- Improve the returning and storing energy system replacing the nonlinear spring to a more optimal system like a pneumatic or hydraulic circuit with a reservoir capable to store and deliver the energy on the entire cycle.
- Include a tidal adjustment to regulate the wire depending on the tide stage.

The primary use is as single generator unit but it can work together in group with others units making it modular and expandable. Thanks to it is possible to build generation farms using this device as generator, but in this case the voltage must be increased in order to transport the electrical energy far away to the consumption location. For that reason a transformer must be added into the farm to raise the voltage output and avoid high losses on transport stage.

Finally the real device's performance will be improved or decreased depending on the location of the generator, because the wave's energy is not a constant over the world.

For that reason is important to seek the best places to invest on this technology, globally the best places are situated far away from equator and near to the poles where the wave energy is more intense. The best world places are located on west Europe coasts, west Canada and USA coasts, east Japan and Russia coasts and all the coasts near to the South Pole.

6 Acknowledgments

So many people leaved their footprint in this project but specially three of them with a significant contribution:

- Thanks to Cali Izquierdo for your support, not only in this project, during all the degree length.
- Thanks to Victor Balasch for make the way until here easier, faster and entertained with your friendship.
- Thanks to Manuel Izquierdo, helping with the project's English orthography.

Finally thanks to all the classmates for the teamwork in challenging times, and all the electrical specialty teachers helping us with their enthusiasm on this abstract subject.

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